THE ELEMENTS OF HYDROLOGY

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BY

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SECOND EDITION REVISED

NEW YORK
JOHN WILEY & SONS, INC.
LONDON: CHAPMAN & HALL, LIMITED

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Stanhope Press
F. H. GILSON COMPANY
BOSTON, U.S.A.

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PREFACE TO SECOND EDITION

Since the first edition of this book was published ten years ago, much has been written on some phases of hydrology. In the present edition about forty pages of new material, some of it necessarily in very condensed form, and a large number of specific subject references to recent publications have been added. General references at the end of chapters have purposely been omitted, as in the earlier edition, because the author has usually found them an aggravation rather than an aid. Suggestions received from a number of teachers of hydrology have been embodied in this revision, as far as possible, and the author gratefully acknowledges the assistance rendered.

The conclusions resulting from the extensive rainfall studies of the Miami Conservancy District are presented in the form of charts and diagrams for convenient utilization. Studies by Marston relating to the area covered by intense rainstorms of short duration have also been added.

From the author's study of the original Weather Bureau records of self-registering gages at St. Paul and Minneapolis, average corrections have been derived, to apply to excessive precipitations during 5-minute to 120-minute intervals, computed from the accumulated amounts of precipitation for each 5 minutes, during all storms published in the annual reports of the Chief of the Weather Bureau, in order to reduce such precipitations to the actual maxima occurring in any part of the storm for the given time intervals.

Horton's and Parshall's new formulas for evaporation and a condensed statement referring to Horton's excellent interception studies have been added. The fact that the author does not include interception in transpiration but considers it a phase of evaporation from land areas is pointed out because that fact has repeatedly been misstated.

The conclusions from Houk's valuable runoff studies at Dayton are summarized; Vermeule's equations for runoff are given in full; and the Minnesota runoff formulas, together with a table of observed flood discharges from drainage basins, ranging from less

than one square mile to over a million square miles in area, are included in the chapter on Runoff.

Allen's salt-velocity and Gibson's pressure-wave methods of measuring discharge are briefly noted.

The author trusts that the revisions and additions will be found useful.

A. F. M.

MINNEAPOLIS,
January, 1928.

PREFACE

The science of hydrology, although it has received relatively little attention in the United States until recent years, has a wide field of application. It is fundamental to the solution of many problems in water-power, water-supply, sewerage and sewage disposal, drainage, irrigation, navigation, and flood protection and prevention. Although basic to a large field of engineering science, hydrology itself is founded upon numerous other sciences, as well as upon a large body of physical data peculiar to itself.

Although the material presented in the following pages represents considerable effort, it is far from complete, and only the urgent need for a book which should set forth at least the most important physical bases and applications of the fundamental principles underlying the science of hydrology, induced the author to prepare the material for publication at this time.

The book is intended to be of assistance to professional men, teachers, and students of engineering. It has been prepared with the view of clearly setting forth fundamental data and considerations rather than of providing either a text or a reference book, and, of course, not a handbook. It will be years before the fundamental principles and facts underlying the science of hydrology have received sufficiently general acceptance to permit their condensation into handbook form.

The data and computations presented in this book were prepared with the assistance of a paid office staff and are believed to be free from material discrepancies. While all totals and summaries of important data were checked, and many were double-checked, using the adding machine, the work of tabulating the tens of thousands of precipitation records, for example, was not duplicated, because the possibility of errors being made

in the compilations which could affect the final conclusions was so small as not to warrant the expense of the extra work.

Endeavor has been made to acknowledge the source of all previously published data wherever these are first introduced. Valuable assistance was rendered and courtesies were extended by several Departments of the Government, particularly, the Weather Bureau, the Department of Agriculture, and the Geological Survey; and also by the University of Minnesota, the American Society of Civil Engineers, Engineering News, Engineering Record, and by numerous other publications and individuals.

Acknowledgment is also due the author's assistants, Mr. George M. Shepard, Mr. E. Dow Gilman, Miss Edna Busse, Mr. W. J. von Eschen, and others, for loyal and capable service in the preparation of manuscript. Some of these assistants gave their undivided attention to this work for several months.

The author also appreciates the work done by Prof. C. W. Nichols and Mr. M. W. Hewett in connection with the proof reading.

ADOLPH F. MEYER.

MINNEAPOLIS, MINN.,
January, 1917.

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CHAPTER I

INTRODUCTION

Definition of Hydrology. — Briefly stated, hydrology is the science which treats of the phenomena of water in all its states; of the distribution and occurrence of water in the earth's atmosphere, on the earth's surface, and in the soil and rock strata; and of the relation of these phenomena to the life and activities of man.

Present State of Hydrology. — Hydrology is essentially a new science. It is founded upon other and better-established sciences, such as meteorology, geology, agricultural physics and chemistry, and botany, besides upon a rapidly growing body of physical data peculiar to itself. Our present knowledge of the subject is indeed fragmentary and incomplete and is scattered throughout the literature of engineering and the other sciences mentioned. The complete lack of books on the subject of hydrology itself attests the formative character of the science. No guide posts but individual judgment indicate the mode of treatment to be followed or the field to be embraced in the present treatise, and the author freely acknowledges failure to attain his ideal and the need for early and thorough revision and extension. He trusts, however, that the material and methods of analysis presented will be found serviceable in both office and class-room.

Most of the phenomena of hydrology are exceedingly complex, and to the casual observer the irregularities and apparent inconsistencies are often so great as to make the existence of fundamental laws and cause-and-effect relationships seem hopelessly obscure and even completely improbable. Not with-

standing this seeming confusion, however, the occurrence of all natural phenomena will be found based upon law and order, if one can only analyze the conditions surrounding these phenomena and evaluate the varying influences and effects of these conditions in each instance.

In working out the projects of hydraulic engineering, the engineer faces a real situation that must be met notwithstanding the incompleteness of our knowledge of the fundamental principles and data of hydrology. However inadequate the data, he is forced to draw conclusions and make recommendations which often involve considerable expenditures. Moreover, the hydraulic engineer cannot safeguard the situation presented by inadequate data by introducing the usual factor of safety employed in structural work, because if he did nearly all the projects of hydraulic engineering would become impracticable. Though forced to deal with admittedly incomplete hydrological data and uncertain, future occurrences of natural phenomena, he is usually limited to factors of safety of about 1.25 to 1.50. The structural engineer, on the other hand, dealing with elaborate test data and material produced according to specifications and under supervision, employs factors of safety of 4 to 5. Although in most cases human life is not so directly concerned in the success of the projects of hydraulic engineering as it is in those of structural engineering, the probabilities of financial loss are usually greater in the former field. Since all of these projects are, to a greater or less extent, based upon the data and principles of hydrology, and since the allowable factor of safety or "factor of ignorance" is small, the need for a knowledge of hydrology is apparent.

Application of Hydrology. — Each year sees new improvements in the structures and machinery involved in the control and utilization of water, but the physical data and principles upon which the science of hydrology is founded, when once fully determined, will ever remain unchanged. These fundamental data and principles find some measure of application in

nearly every field of engineering and are, indeed, basic to several large and important fields. Some of these fields of engineering are most intimately concerned with the amount and rate of rainfall and the methods of disposing of the excess water which, from their viewpoint and within the confines of their field, can serve no useful purpose. Such disposal of water may involve the prevention of floods and the drainage of agricultural lands or of urban communities. Other fields of engineering are concerned with the conservation of the rainfall which runs off from the land or percolates through the soil into the underlying strata, and the utilization of this water for domestic and manufacturing purposes, for the irrigation of arid lands, for the development of power, and for the transportation of freight and passengers. In the development of cities, engineers are continually concerned with the flow of streams. Among their problems are the relation of stream flow to water-front improvements, the disposal of sewage and waste, and the control of flood waters. Such, in brief, are *a few* of the fields of engineering to which the science of hydrology is more or less basic.

Although hydrology has not, heretofore, been generally considered a fundamental science, yet it is a fact that the structures involved in hydraulic engineering projects far less frequently fail to serve their purpose because of fundamental defects in structural design than they do because that design is not based upon correct hydrological principles and observations.

Although the specialist in many branches of the engineering profession may not always, in the solution of his particular problems, require a broad knowledge of the fundamentals of hydrology, he will, nevertheless, often derive considerable assistance from at least a general familiarity with the natural phenomena that affect the occurrence, distribution, and disposition of water on the surface of the earth.

The development of our country has kept hydraulic engineering projects and allied problems involving the principles of hydrology almost continually before the public. This has given

rise to a great clamor for public funds for river improvement, reservoir construction, and drainage, and much misinformation and misconception regarding the feasibility of such projects has been manifested at times. As a member of his community the engineer possessed of a knowledge of even the elements of hydrology may wield an important influence in molding public opinion regarding the general feasibility of such projects, even though the details of the problems involved may be quite outside of his own specialty and may require thorough analytical study before their solution is finally determined. Through this influence on public opinion the engineer may assist not only in conserving a natural resource, so far as practicable, but also in conserving the tax-payer's money.

Among the principal controversial subjects of hydrology are those concerning the interrelationship of forests, reservoirs, drainage and stream flow. The lay mind associates the removal of forests and the drainage of lands with destructive floods, without reference to the cause of floods on different streams or the great variation in flood-producing characteristics of different watersheds. No general deductions of universal applicability can be made. *Every stream is a problem in itself.* It follows, therefore, that much detailed observation and study are necessary to establish fundamental hydrological principles. Observations indicate that forests may both increase and decrease floods; that drainage may both increase and decrease stream flow. The conditions under which these effects may prevail are discussed later.

Another subject regarding which much general misinformation exists is that of the prevention of floods by storage reservoirs. Projects for the impounding of flood-water so as to prevent streams from over-flowing their banks and the later utilization of this stored water for power development and for increasing the depth of navigable streams, appeal to many people as great measures of conservation, whereas they are usually good opportunities for the waste of public funds. Destructive floods sel-

dom occur with sufficient frequency to make their water worth conserving. Such floods are an evil that must be passed on back to the sea as expeditiously and with as little opportunity for doing damage as possible.

Water as a Natural Resource. — The quantity of water with which mankind is concerned must always remain substantially the same, but its occurrence and its distribution over the surface of the earth is continually changing. As an article of use and consumption, water is one of those few natural resources the supply of which remains substantially undiminished because, through the action of natural laws, water is continually performing an ever-recurring cycle of evaporation, condensation and precipitation, *ad infinitum.*

The sun's energy vaporizes the water from the surface of the earth. The vapor thus formed is lighter than the dry gases of the atmosphere, and hence tends to rise. Aided by convection currents, the water vapor moves from place to place and upward through the air. On rising, it encounters a rarified atmosphere and expands. The energy required for the work of expansion is drawn from the air itself, resulting in a cooling and ultimate condensation of some of the vapor which falls to the earth again as rain. The precipitated water then starts on its way back to the ocean. Some of it is lost through evaporation and some is used by growing plants. The portion flowing over the earth's surface and through the rock strata furnishes the water for consumption, for power and for transportation. The most complete conservation of water can be secured only by its fullest utilization, for so long as the sun shines, this natural resource is continually being replenished. The intelligent control and conservation of water must be based upon the fundamental principles of hydrology.

The Subject Matter of Hydrology. — The field of hydrology, like that of most other sciences, is not sharply demarcated. The subject matter is largely drawn from the sciences upon which hydrology is founded. In consequence, it is difficult to

determine, in a book of this kind, what material shall be used and what shall be excluded.

In developing the subject the author has followed what from his viewpoint, acquired through about fifteen years of experience with the practical problems of hydraulic engineering, appeared a logical sequence. Not only the data and considerations having direct and frequent application have been included, but also those facts and principles which are fundamental to a more detailed study of hydrology itself. Subject matter which did not appear to meet either of these requirements was omitted, since this volume is not intended to serve as a comprehensive reference book covering every phase of the subject of hydrology.

Since the sun's heat and the earth's atmosphere are really the first causes in the natural phenomena which give rise to the problems of hydraulic engineering, these subjects have been treated first, in some detail. Solar radiation is the source of the heat of the earth that causes evaporation and transpiration and the circulation of the air with its vapor content. Unequal heating of the earth's surface gives rise to the great air movements that largely determine our rainfall, our floods, and our droughts. These larger atmospheric movements and the secondary circulation to which they give rise, together with the attendant phenomena, are discussed. This is followed by a consideration of water in its various states and their properties, with special emphasis on the characteristics and the effects of the water vapor of the atmosphere.

The manner in which water is precipitated out of the air, how the precipitation is measured, and the observed rates of precipitation are treated quite fully. Many tens of thousands of rates of rainfall are summarized in a manner permitting their true significance to be readily grasped, while still preserving the original data in sufficient detail to permit of their further analysis, and the making of independent deductions. The most severe rainstorms in different parts of the country are mapped for use in determining channel and spillway capacities. Exces-

sive rates of rainfall are treated in considerable detail and new formulas are presented, giving the rates which will be exceeded with average frequencies of once in from one to one hundred years.

The subject of evaporation from water surfaces is next treated. The factors modifying it are discussed and their relative importance is indicated. Some of the best observed data are presented, both in tabular and in graphical form, and curves and formulas are suggested for practical application. Evaporation from water surfaces is substantially continuous at a uniform rate. Evaporation from land areas is so irregular as to be almost intermittent. The amount of water evaporated from land areas depends both upon the rate of evaporation, and upon the evaporation opportunity as represented by the available supply of moisture, hence the modifying factors are discussed separately. Considerable emphasis is laid upon percolation and capillary action in different soils and on the effects of vegetation and drainage on evaporation losses. This is followed by a discussion of transpiration, its amount and the factors that modify it, viewed from the standpoint of the effect of transpiration upon the amount of precipitation that will find its way into the streams. The effect of the character of the soil on the amount of water available for percolation, transpiration, and evaporation in different soils is treated, and a new method is presented for determining soil moisture in terms of inches of water per foot depth of soil under field conditions.

Consideration of underground water and its rate of motion is followed by a discussion of runoff. This represents the residual precipitation after evaporation, transpiration, and deep seepage losses have been supplied. In dealing with the factors that modify runoff the flow of streams is divided into surface flow and seepage flow. Typical watersheds are studied with a view to bringing out the extent to which watershed characteristics are reflected in the hydrographs of streams. Floods due to rainfall and snowfall are analyzed to show the cause of floods

and the relative effects of the various flood-producing characteristics of different watersheds.

The factors modifying the low-water flow of streams are next discussed, and some observed low-water stream-flow data are presented. The fundamental principles and essential facts regarding the various methods of obtaining stream-flow data are discussed, but no attempt is made at a comprehensive treatment of the subject. For further information the reader is referred to Hoyt & Grover's "River Discharge." Methods of supplementing stream-flow data by computing runoff from rainfall and other physical data are presented, and finally the modification of stream flow by storage is discussed. The cost of storage, the factors determining the desirability of reservoir sites, losses from reservoirs and the storage of water for municipal purposes, for irrigation, logging, navigation, flood prevention and power purposes are specifically treated. Mass curves and frequency curves are explained, with illustrations of the use of typical curves in water-power studies. This is followed by a statement of the extent to which the storage of water for the various purposes conflict. Finally, reference is made to the storage of water below ordinary high-water mark in those portions of the country where the law of riparian rights holds.

The arrangement of the subject matter which has been followed appeared logical to the author and he trusts it may also be found convenient and conducive to a clear understanding of the subject by those who may have occasion to use the book.

CHAPTER II

THE ATMOSPHERE: ITS TEMPERATURE, PRESSURE AND CIRCULATION

Use. — The most important direct use of the atmosphere is its function in providing plants and animals with the carbon dioxide and the oxygen essential to the chemical reactions of life, and in preventing the rapid radiation of heat at night which would make the earth uninhabitable. Minor, indirect uses of the atmosphere are its mechanical power to propel wind mills and boats, to distribute seeds and to sustain the flight of birds and man. From the viewpoint of hydrology, perhaps the most important function of the atmosphere is the transportation of water vapor and the absorption of radiant energy.

Composition. — At sea-level elevation the atmosphere is composed of substantially 78 per cent of nitrogen, 21 per cent of oxygen, .9 per cent of argon, about .03 per cent of carbon dioxide, and a greatly varying amount (from less than 1 per cent to 5 per cent) of water vapor, in addition to small amounts of hydrogen, helium and a few other unimportant gases. Above an altitude of about fifty miles the atmosphere appears to be composed primarily of hydrogen, which is believed to be continually escaping from the earth's atmosphere into space. The composition of the earth's atmosphere is shown graphically in Fig. 1, taken from an article by W. J. Humphreys, in the Bulletin of the Mount Weather Observatory, 1909.

When the percentage of oxygen in the atmosphere drops below 18½ the candle flame dies out. The percentage of carbon dioxide is considerably greater over cities than in the country,

particularly in calm weather. As high as five to ten times the normal proportion of carbon dioxide has been found in crowded buildings. A continuous supply of about 2000 cubic feet of fresh air per hour is required for each person in order to maintain a desirable standard of purity.

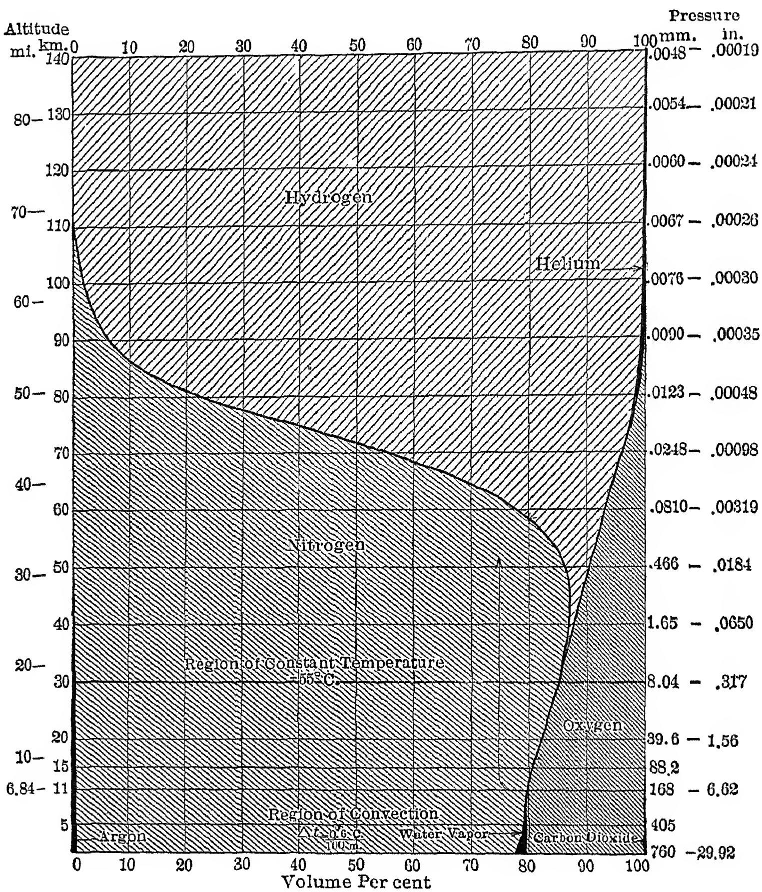


FIG. 1. — Distribution of Gases in the Atmosphere (after Humphreys).

The several gases of the atmosphere exert substantially no influence over each other except that the dry gases affect the rate of diffusion of water vapor. These gases exist purely as a mechanical mixture, each independent of the others;

the nitrogen, for example, exists as an atmosphere enveloping the earth exactly as if the oxygen and the other gases were not present.

Considering an average dry atmosphere as having a density of one, the density of nitrogen is .97, oxygen 1.11, carbon dioxide 1.52 and water vapor .62. Nitrogen occurs in measurable quantity to an elevation of about 35 miles above the surface of the earth, and oxygen to an elevation of 30 miles. Carbon dioxide practically disappears at 10 miles, and water vapor at 12 miles above the surface of the earth. We know, however, from the appearance of meteors and from the phenomenon of diffraction, that the atmosphere, even though rare, extends to a very much greater elevation.

Properties. — The atmosphere has weight, as manifested by the height of the column of mercury which it supports in the barometric tube and the height of the column of water which it supports below the bucket of a pump; it is also highly compressible, as manifested by the action of the air pump and the inflated rubber ball. Each gas of the atmosphere is compressed by the weight of the layers of gas above, and consequently is denser at sea level than at all points above that elevation. If it were not for changes in temperature, the density of the dry gases of the atmosphere would be entirely dependent upon the volume of each particular gas above the point under consideration. According to Boyle's law, when the pressure on a given volume of gas is doubled, without change in temperature, the volume of the gas is halved. When the temperature of a gas is changed, the volume of the gas, according to Charles' law, increases approximately $\frac{1}{273}$ for every increase of one degree in temperature, Centigrade. By means of these two laws and observed temperatures, the density of the dry gases of the atmosphere at any given elevation can be determined.

The specific heat of the dry gases of the atmosphere, measured under the conditions of constant pressure, is .24, and that of water vapor is .48 times that of water in the liquid state.

Amount of Water in Atmosphere. — The amount of water vapor present in the atmosphere varies greatly from time to time, but the dry gases do not change materially in quantity from season to season. During the winter months, in the Northwest, no matter how thoroughly saturated the air may appear, the total amount of moisture present in the atmosphere represents less than half an inch of rain. During the summer months, on the other hand, it is not unusual for the total amount of moisture in the atmosphere to equal about three inches of rain. Under ordinary weather conditions about half these amounts of moisture are present.

The maximum amount of moisture which could possibly be precipitated from the atmosphere at any one time is, naturally, the total amount of moisture which the atmosphere contains. As a matter of fact, however, only that portion of the moisture which can be precipitated as the result of the change in temperature accompanying the rise of the water vapor to the upper cloud level can fall as rain. This amount, uniformly distributed, represents about one-tenth inch of rainfall in December and six-tenths inch in June.

The only reason why, over a restricted area, larger amounts of precipitation than those above mentioned ever occur, is because of the fact that part of the rainfall is derived from moisture present in the atmosphere over adjoining land or water areas which is brought in from all sides, by the wind, to the restricted low-pressure area under which the maximum precipitation occurs. Heavy rainfall can occur only over small areas. General, well-distributed rains are nowhere excessive. This phase of the subject is discussed in detail in a later chapter.

Distribution of Water Vapor. — The water vapor is not distributed through the atmosphere in accordance with the laws of Boyle and Charles because of the fact that under the ordinary conditions of the atmosphere it exists as a nearly saturated vapor, which, with relatively small change in temperature and pressure, will be condensed and partly precipitated. Under natural conditions the other gases of the

atmosphere never meet with sufficient increase in pressure, and decrease in temperature to reach the liquid or the solid state. Hence, the distribution of water vapor through the atmosphere is determined primarily by temperature.

As the amount of water vapor present in the atmosphere is dependent mainly upon its temperature, the subject of temperature will be considered before the distribution of water vapor in the atmosphere is further discussed. It may be remarked at this point, however, that about half of the total moisture present in the atmosphere is found below an elevation of about 6000 feet, and less than one tenth of it occurs above an elevation of 20,000 feet.

Temperature

Source of All Heat. — The temperatures with which the science of hydrology is primarily concerned are the temperatures of the air, the water and the soil. Changes in temperature merely represent changes in the great velocity with which the molecules constituting the various gases, or liquids, or solids are moving back and forth over their minute paths. The ultimate cause of all changes in temperature is the sun. Radiant energy reaches us from the sun in the form of waves having various lengths, but even the longest are inconceivably short. These waves travel at the rate of 186,000 miles per second. A portion of the radiant energy from the sun is absorbed by the atmosphere during the passage of the sun's rays through it. The radiant energy so absorbed increases the rate of vibration of the molecules of the gases of the atmosphere — that is, increases its temperature. The portion of the energy which reaches the earth's surface accelerates the motion of the molecules of water, soil and other material, and hence raises the temperature of those objects. The surface of the earth, in turn, radiates heat outward, thus again increasing the temperature of the air above it.

The heat absorbed by water areas of given depth for a given

rise in temperature is about four times the amount absorbed by equal land areas and to equal depths for the same rise in temperature. Various soils also exhibit different heat absorbing and reflecting properties. Sand, for example, will absorb about twice as much heat as humus and about one and a half times as much as clay. On the other hand, during the night, humus will quickly radiate into the atmosphere even the little heat absorbed during the day, making highly vegetable soils essentially cold soils, and sandy soils essentially warm ones.

Effect of Water Vapor on Solar Radiation. — The water vapor in the atmosphere virtually governs the portion of the solar energy which is absorbed during its passage to the earth. This is due to the great changes in the water vapor content of the atmosphere and its high specific heat. Just twice as much heat energy is required to raise a given weight of water vapor one degree in temperature, as is required to raise the same weight of dry air an equal amount. To raise the temperature of liquid water one degree requires substantially twice the amount of heat energy required to raise the same weight of water vapor an equal amount.

The presence of water vapor in the atmosphere also materially influences the rate at which heat is radiated back into space by the earth during the night time. Clear nights are relatively cold nights; cloudy nights are invariably warmer than they would be if the moisture in the atmosphere did not prevent the rapid radiation of heat from the earth's surface.

The amount of solar radiation or insolation received at the surface of the earth varies greatly with the altitude of the sun, mainly because of the difference in the thickness of the layer of atmosphere through which the rays of the sun must travel. At sunrise, for example, the sun's rays travel through approximately 35 times the thickness of atmosphere traveled through at noon on a summer day. For this reason the amount of solar radiation received by the surface of the earth varies greatly with altitude, and also with latitude.

It has also been observed that extensive forest fires and volcanic eruptions, through the dust which is emitted into the atmosphere, substantially reduce, for such considerable periods of time as a year, even, the amount of solar radiation received in some localities.

Measurement of Solar Radiation. — The little glass globe and its revolving black and white vanes, frequently seen in opticians' windows, is a familiar object to all. This principle of the absorption of heat by black objects and its reflection by white objects is utilized in the construction of pyrheliometers, — instruments used for the measurement of solar radiation. Pyrheliometers consist, essentially, of black and bright bulb thermometers placed in a vacuum. In general, the black thermometer registers from 50 to 60 degrees higher than the bright thermometer. On mountain tops in the bright sunshine, the temperature of the black bulb thermometer has reached over 230 degrees. The solar radiation temperatures in the Polar regions are surprisingly high, largely on account of the absence of water vapor. It has been found, for example, that in the Arctic region, with the altitude of the sun at only about 30 degrees, the mean black bulb temperature in June was only about 14 degrees, Fahrenheit, less than that at Madras, with an almost vertical sun.

Amount of Solar Radiation Received. — The amount of solar radiation received on a clear summer day on each square yard of the earth's surface represents about 1.2 horsepower. Fig. 2, reproduced from the August, 1914, Monthly Weather Review, is a graph of the solar radiation received at Mount Weather Observatory, Virginia, Latitude 39° 4′ N., on May 8, 1913. Two curves are shown in this diagram. The upper curve shows the total amount of solar radiation received from hour to hour, and the lower curve shows the amount of sky radiation received at the same time. By sky radiation is meant the energy radiated from the sky as recorded by the pyrheliometer when completely shielded from the direct rays of the sun.

The amount of solar radiation received at the surface of the earth during the varying seasons and in various localities is of tremendous importance in the science of hydrology because

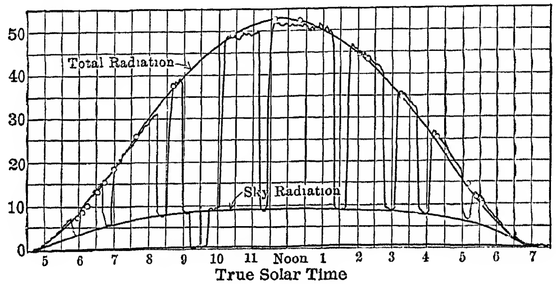


FIG. 2. — Daily Variation in Solar Radiation, Mount Weather, Va., May 8, 1913.

of its effect on the cycle of evaporation, condensation and precipitation of water, and on the growth of plants.

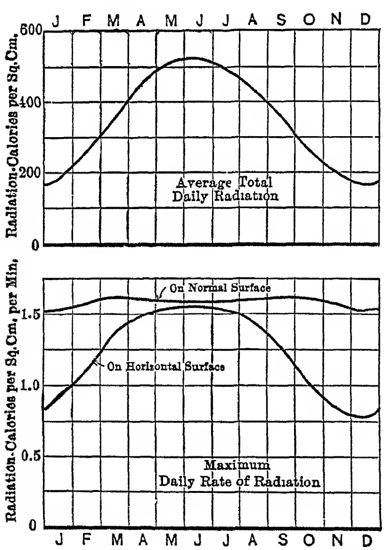


FIG. 3. — Annual Variation in Solar Radiation at Mount Weather, Va., Latitude 39° 4′ N.

The upper curve of Fig. 3, prepared from data published in the Monthly Weather Review, shows the average total daily amount of solar radiation received during the different months of the year, at the Government Observatory, at Mount Weather, Virginia, during 1912, 1913 and 1914. The lower curves of the same Figure show the maximum daily rate of radiation at Mount Weather for each month of the year, based on observations taken since 1907.

The solar radiation received on a surface perpendicular to the rays of light, and on a horizontal surface are both shown. It is worthy of note that the maximum radiation received on

a normal surface is substantially the same in December as in June. The intensity of the sun's rays on a clear December morning is a matter of common observation.

Fig. 4, prepared from data given by Moore,* shows the relative total annual amount of solar radiation received at the outer atmosphere in various latitudes, and the portion which reaches the earth's surface, together with the portion absorbed by the earth's atmosphere.

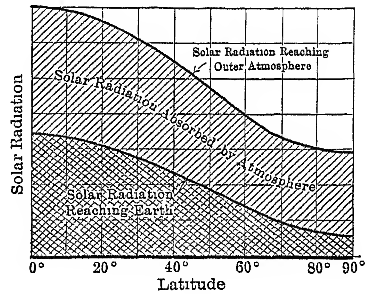


FIG. 4. — Relative Total Annual Solar Radiation Reaching Earth.

It will be noted that while the amount of heat and light received from the sun at the outer atmosphere is only about $2\frac{1}{2}$ times as great at the equator as at the poles, the amount actually reaching the earth's surface in the equatorial regions is 6 times as great.

Fig. 5 shows the relative total monthly radiation as calculated by Angot to reach the earth at the various latitudes, assuming that, on an average, 40 per cent of the daily radiation is absorbed. As a matter of fact considerably more is absorbed, but on account of the varying degree of cloudiness the true total average absorption by the atmosphere is difficult of determination.

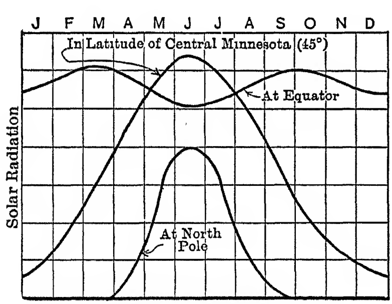


FIG. 5. — Relative Monthly Mean Solar Radiation Reaching Earth.

The reason for the rapid growth of all vegetation during the short summers of the middle latitudes is forcibly brought to one's attention by the preceding diagrams. The amount of water used by plants is, in general, proportional to their growth.

* Moore, W. L., Descriptive Meteorology.

The water used by plants is not available as a runoff; consequently solar radiation becomes a factor influencing stream flow. This phase of the subject will be further discussed in a later chapter.

The following table * shows the aggregate number of hours of daylight, twilight and night at the equator and at the poles.

At the equator	At the poles
4407 hours day 864 " twilight 3495 " night	4450 hours day 2403 " twilight 1913 " night

It has been calculated that the amount of solar heat received by the earth in a year is sufficient to melt a layer of ice 141 feet thick, or to evaporate a layer of water nearly 18 feet thick, covering the whole earth's surface. If it were not for the presence of the atmosphere, however, and its effect in preventing rapid radiation at night, the temperature of the surface of the earth, in spite of the large amount of heat received from the sun during the daytime, would drop to about 325 degrees below zero, Fahrenheit.

In perfectly clear weather, with the sun directly overhead, about 75 per cent of the solar radiation reaches the earth's surface, the remaining 25 per cent being absorbed by the atmosphere. The heat rays are much more readily absorbed by the atmosphere than the light rays, so that when the sun is near the horizon we may receive considerable light but little heat. In latitude 45 degrees a little over half of the solar radiation is absorbed by the air. According to Abbot, considering the earth as a whole, 76 per cent is absorbed.

Refraction. — There is a period each day for an hour or more before sunset until sometime after, when the heat received by the earth from the sun is equal to the amount radiated by the earth into space. A similar though shorter period

* Waldo, Frank, Elementary Meteorology.

occurs in the morning. This is the period best suited for astronomical observations and accurate survey work. During these periods objects appear steady in the object glass of the telescope, as is well known to all surveyors. The unsteadiness of objects during the daylight hours is caused mainly by the unequal refraction of light. Snow always has a particularly bad effect.

Temperature Data. — Temperature data for the United States, which are of great service in the field of hydrology, are collected and published by the Weather Bureau of the Department of Agriculture. Observations are made at a total of nearly 6000 stations. Only about 200 of these, however, are paid observer stations, equipped with a full set of instruments and at which all the principal phenomena relating to the weather are observed. About 4200 stations are known as "coöperative observer stations," at which the observer receives no compensation except in the form of certain publications of the Weather Bureau. The remaining stations are special paid stations at which only certain observations are made relating to crop conditions, river stages, etc. The coöperative observers record only rainfall and maximum and minimum temperature, and make notes regarding the general condition of wind and weather, early and late frosts, appearance of aurora, etc. Fig. 6 shows a typical coöperative observer station. The thermometers are located in the shelter and the rain gage is at the right.

Thermometers. — The maximum thermometer used by the Weather Bureau consists of a long graduated mercury tube and bulb. Just above the bulb the tube is constricted so that when the mercury contracts after having reached its maximum height, the column breaks at the constricted section, leaving the upper portion registering the maximum temperature within a few tenths of a degree. When the thermometer is subject to slight jarring or vibration, the column breaks sooner, and hence registers more accurately, than when it is kept perfectly quiet.

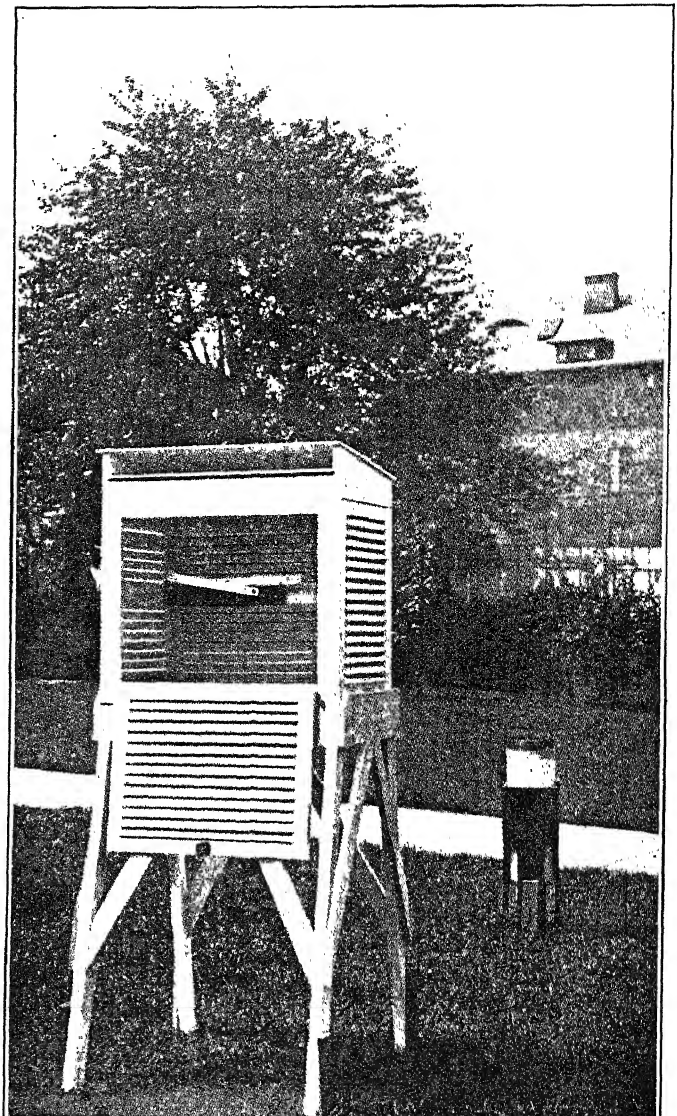


FIG. 6. — Typical Coöperative Observer Station.

The minimum thermometer is filled with alcohol. In the tube of the thermometer an index is floated which, as the alcohol contracts, is carried downward by the surface tension of the liquid. When the alcohol expands after having reached its minimum temperature, the liquid does not carry the index up with it. The accuracy of such a thermometer is about half a degree. Both maximum and minimum thermometers are kept in a nearly horizontal position.

Where a continuous record of temperature is desired, a recording thermometer, such as the "Thermograph" of Fig. 7, is used.

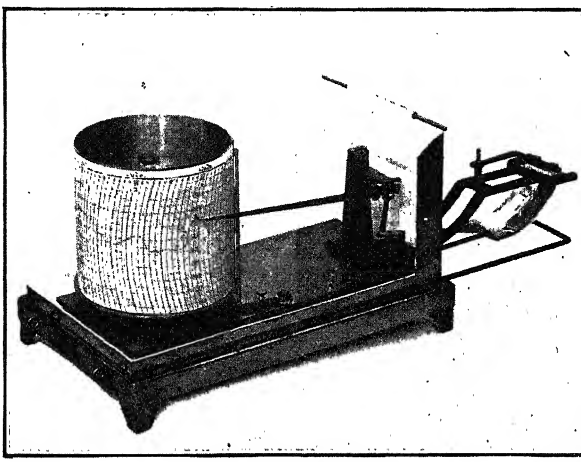


FIG. 7. — Thermograph.

Daily Mean. — The maximum air temperature usually occurs soon after noonday, and the minimum air temperature usually occurs just before sunrise. It has been found that, on an average, the mean of the maximum and the minimum temperatures in any 24-hour period is about .4 to .5 degrees less than the true mean daily temperature. The mean of the 9 A.M. and the 9 P.M. readings is also about half a degree low. The mean of the 8 A.M. and 8 P.M. readings is

about .2 or .3 of a degree low. One fourth of the sum of the 7 A.M. plus the 2 P.M. plus twice the 9 P.M. temperatures is almost exactly equal to the true mean daily temperature. A single day's observations, of course, may depart considerably from the above expressed mean relationship.

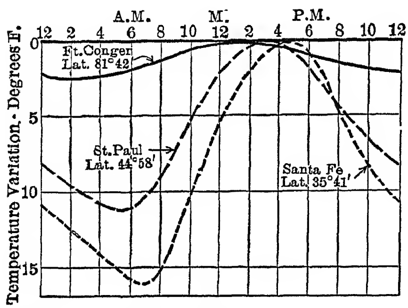


FIG. 8. — Mean Daily Variation in Temperature measured from Maximum.

Daily Variation. — The daily temperature changes on the earth's surface vary greatly with latitude. Inasmuch as the sun shines for 12 hours at the equator and then disappears for 12 hours, it is evident that the daily changes in temperature, other conditions remaining the same, must be greater at the equator than in the regions toward the poles where the sun may shine continuously for days, weeks or even months at a time. This is illustrated by Fig. 8, which shows the mean daily variation in temperature at typical continental stations in various latitudes.

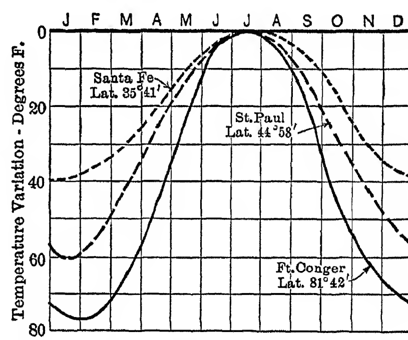


FIG. 9. — Mean Annual Variation in Temperature measured from Maximum.

Annual Variation. — The variations in annual temperature are opposite, in relative magnitude, to the variations in daily temperature. As the sun shines 12 hours a day, each day in the year, at the equator, and shines continuously for days and even months in the polar regions, and then disappears from those regions altogether for an equally long time, it is apparent that the annual fluctuations in temperature, other conditions remaining the same, must be far greater in

the polar regions then at the equator. This fact is well illustrated by Fig. 9.

The mean difference between July and January temperatures in various latitudes north of the equator, according to Hann,* is shown in Fig. 10.

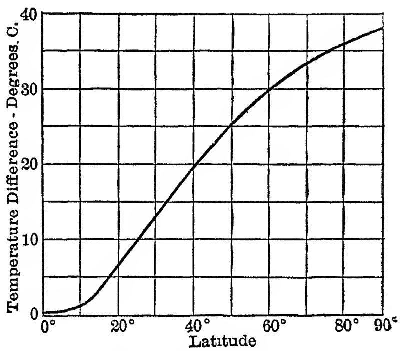


FIG. 10.—Mean Difference between July and January Temperatures in Various Latitudes.

Periodic Variation. — In addition to the daily and hourly changes in temperature and the more or less irregular changes accompanying daily changes in weather, long-term temperature observations indicate a fluctuation in the mean annual temperature over periods of varying length, with indications of 35-year cycles and minor periodic variations occurring in 11-year and $3\frac{3}{4}$-year intervals in synchronism with sun spots and solar prominences.

Extremes of Temperature. — The greatest temperature changes occur in Siberia. According to Hann, the lowest temperature ever observed is $-90.4°$. At Havre, Montana, there has been an extreme range of from $-55°$ to $+108°$. At Poplar River, Montana, a minimum of $-63°$ has been recorded, and at Mammoth Tank, California, a maximum of 128°.

Maps of maximum and minimum recorded temperatures in the United States are shown in Figs. 11 and 12.

Variation with Altitude. — Besides these changes in temperature with the changing seasons, the science of hydrology is intimately concerned with the variations in the temperature of the atmosphere with altitude. The actual observed decrease in temperature is about one degree, Fahrenheit, for every 300 feet increase in altitude. This reduction in temperature with altitude does not continue indefinitely, however, as is well illus-

* Hann, Dr. Julius, Lehrbuch der Meteorologie.

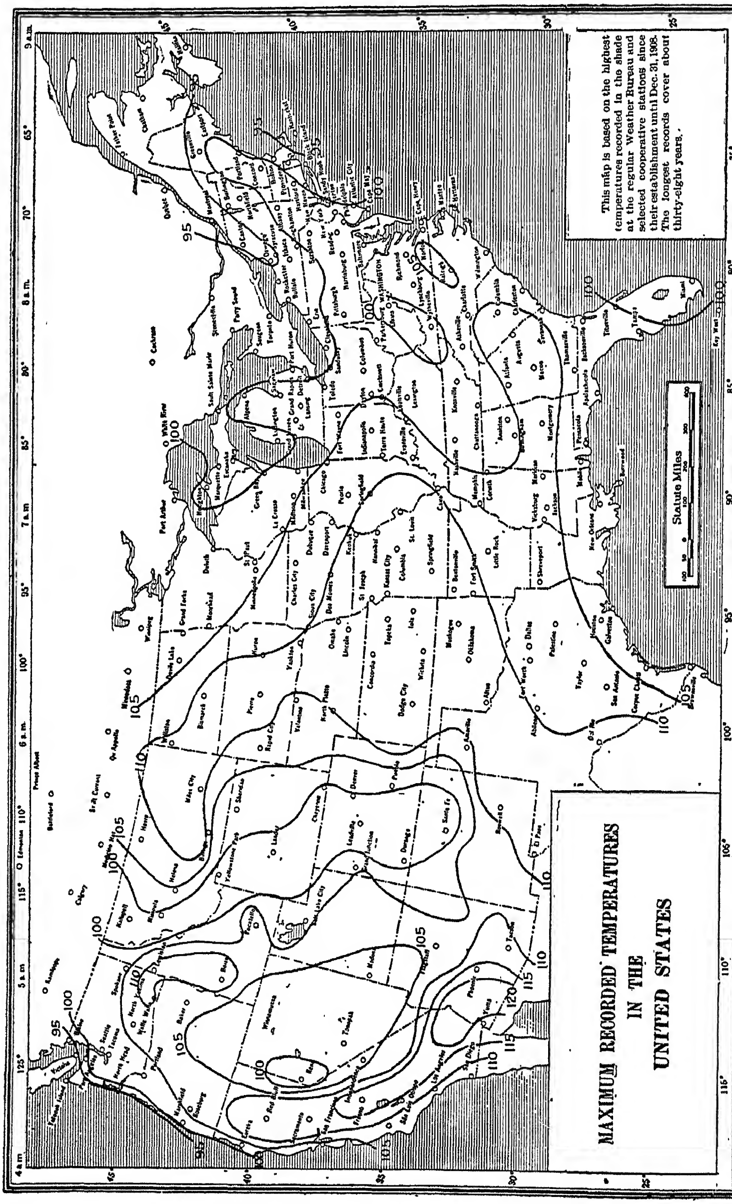

MAXIMUM RECORDED TEMPERATURES
IN THE
UNITED STATES
This map is based on the highest temperatures recorded in the shade at the regular Weather Bureau and selected cooperative stations since their establishment until Dec. 31, 1908. The longest records cover about thirty-eight years.
Statute Miles

FIG. 11.

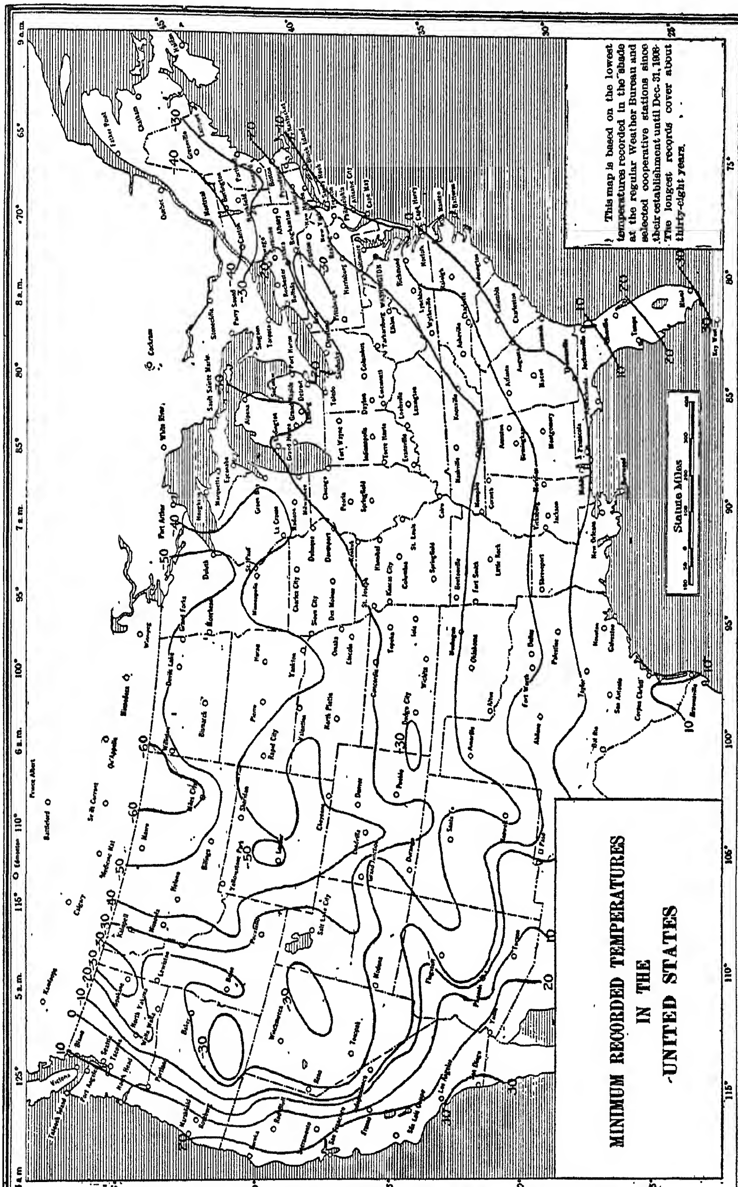

MINIMUM RECORDED TEMPERATURES
IN THE
UNITED STATES
This map is based on the lowest temperatures recorded in the shade at the regular Weather Bureau and selected cooperative stations since their establishment until Dec. 31, 1908. The longest records cover about thirty-eight years.
Statute Miles

Fig. 12.

trated by Fig. 13, reproduced from Sir John Moore's "Meteorology." This figure is a graph of the reduction in temperature recorded by "sounding balloons" sent up to high altitudes.

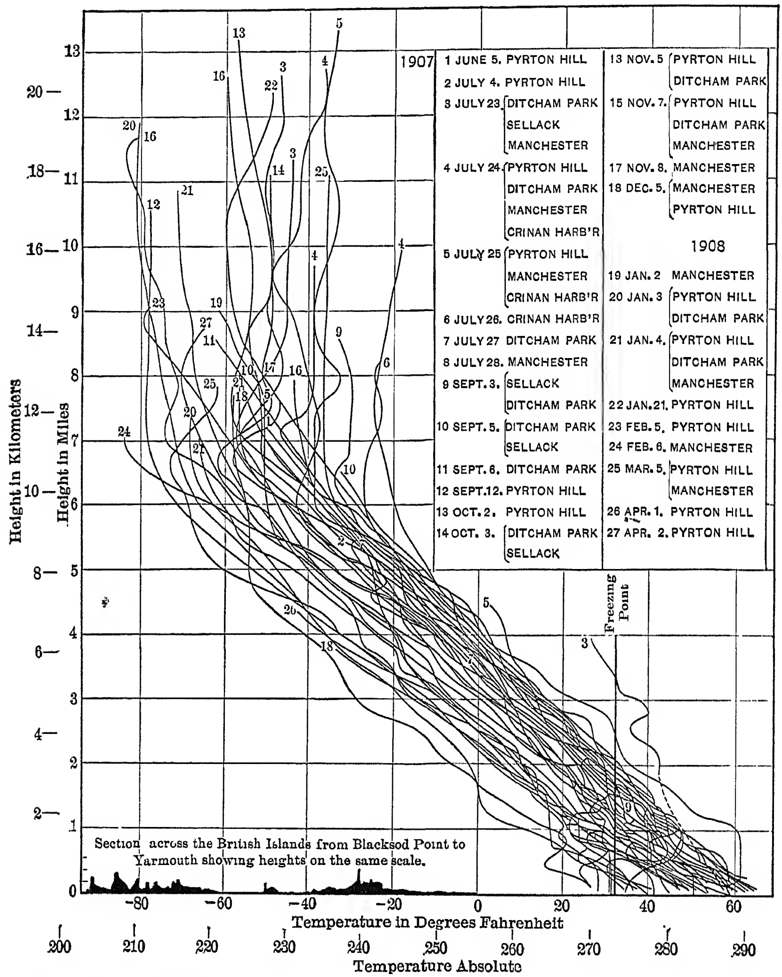


FIG. 13.—Relation between Temperature and Altitude as determined by "Ballons-Sondes" (after Moore).

After an elevation of about seven miles is reached, it will be noted, there is no further reduction in temperature. Below that elevation the average slope of the lines in Fig. 13 indi-

cates an average reduction in temperature of one degree in 300 feet, as previously stated. This reduction in temperature has a tremendous influence on the condensation and precipitation of water. Water vapor moving upward a given distance will encounter a very much greater change in temperature than it could ever encounter in moving the same distance horizontally along the surface of the earth. This phase of the subject will be further discussed in connection with rainfall.

Extending Short-term Records. — Inasmuch as observations of temperature have been made for varying periods of time at the different Weather Bureau stations in the United States, it is frequently necessary to supplement and extend short-term records for the purpose of securing a satisfactory comparison between prevailing temperatures at two given stations. A similar need for the extension of short-term records exists when attempting to prepare maps showing lines of equal temperature, or isotherms. Under such circumstances, instead of using the mean of a varying number of years' records, it is best to compare the mean temperature at the short-term station with the mean temperature for the same period of years at the nearest, similarly located, long-term station, and then to assume that the same relationship would exist between the long-term means at these two stations. In this way the effect of periodic changes in temperature is eliminated, as the short-term mean might cover a series of either warm or cold years.

Pressure of the Atmosphere

Amount and Variation with Altitude. — The force of gravity acting on the molecules of the various gases of the air causes the atmosphere to exert a pressure on the surface of the earth, averaging substantially 14.7 pounds per square inch at sea level. This pressure is equal to the pressure of a water column 33.8 feet high, or a mercury column 29.9 inches high. The usual way of measuring barometric pressure is by means of a column of mercury in a mercurial barometer, although the aneroid

barometer serves a similar purpose. The pressure of the atmosphere diminishes with altitude approximately in accordance with the following simple equation, which serves every ordinary engineering purpose.

$$\text{Log barometric pres. in ins. mercury} = 1.47712 - \frac{\text{altitude in ft.}}{64{,}000}.$$

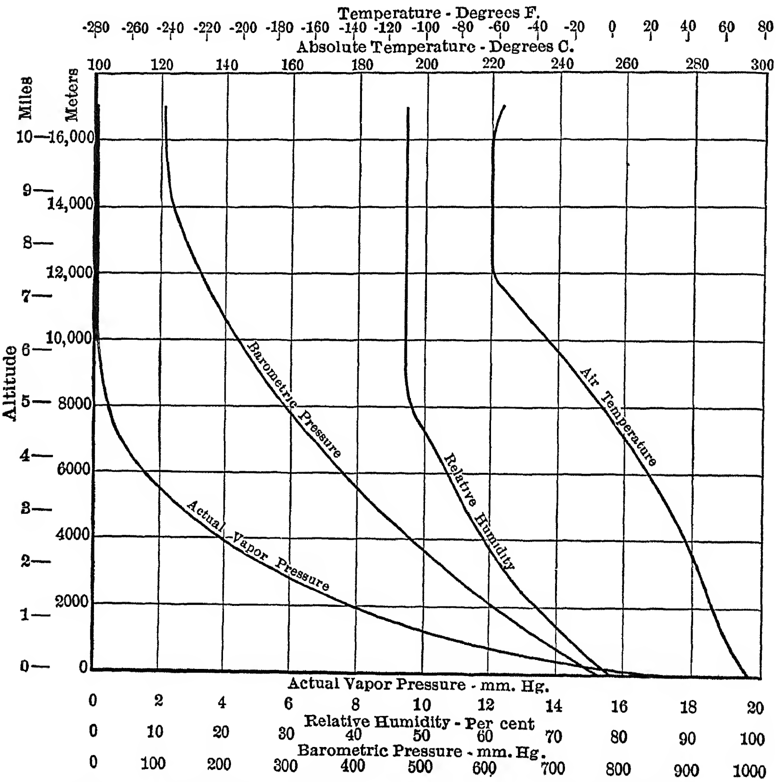


FIG. 14.—Variation of Meteorological Elements with Altitude.

Fig. 14 is a typical graph of the reduction in barometric pressure, temperature, relative humidity and water vapor content of the atmosphere, with increase in altitude, over the Atlantic Ocean in middle latitude in September, 1907. This figure is based on data observed by the U. S. Weather Bureau by means of "sounding balloons."

Table 1 gives the pressure of the atmosphere at various elevations above and below sea level, according to several different measures having common application.

TABLE 1. — ATMOSPHERIC PRESSURE

Inches of mercury	Pounds per square inch	Atmospheres	Feet of water	Elevation in feet	Temperature of boiling point of water, degrees F.
31	15.2	1.03	35.1	−890	213 9
30	14 7	1.00	34.0	0	212 2
29	14 2	0.97	32 9	920	210.4
28	13.7	0 93	31.7	1,880	208 7
27	13.2	0.90	30.6	2,870	206 9
26	12.7	0.86	29.5	3,900	205 0
25	12.2	0.83	28.3	4,970	203.1
24	11.7	0.80	27.2	6,080	201 1
23	11.3	0 76	26 1	7,240	199 0
22	10 8	0.72	24 9	8,455	196 9
21	10 3	0.69	23 8	9,720	194 7
20	9.8	0.67	22 7	11,050	192.4

High- and Low-pressure Areas. — Local heating of portions of the earth's surface results in an expansion of the atmosphere upward, causing some of the air in the upper layers to flow outward and away from the heated area, with a consequent reduction in barometric pressure over that area. During the summer months there is a permanent region of low barometric pressure over northwestern United States and Western Canada, and a region of high pressure over the Pacific Ocean to the west. During the winter months the condition is reversed. These permanent regions of high and low pressure result from variations in temperature, the land area being warmer in summer and cooler in winter. Usually, as soon as the difference in pressure between a low- and a high-pressure area becomes greater than about one half an inch of mercury, a well-defined easterly cyclonic movement sets in. While these storm centers travel over different routes, most of them find their way out through the St. Lawrence valley.

Daily Variation in Pressure. — Aside from the large and irregular variations due to the passage of storms, the baromet-

ric pressure has been found to vary in semi-diurnal waves, as shown in Fig. 15 based on data given by Hann * reaching the principal maximum at about 10 o'clock in the forenoon, and the principal minimum at about 4 o'clock in the afternoon. The secondary maximum occurs shortly before midnight, and

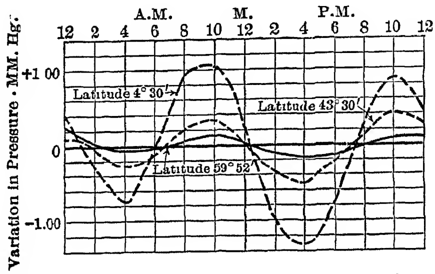


FIG. 15. — Mean Daily Variation in Barometric Pressure.

the secondary minimum at about 4 o'clock in the morning. It will be noted that the daily variation in pressure decreases rapidly from the equator to the poles.

Fig. 16, also based on data given by Hann, shows the effect of clouds on the daily variation in barometric pressure.

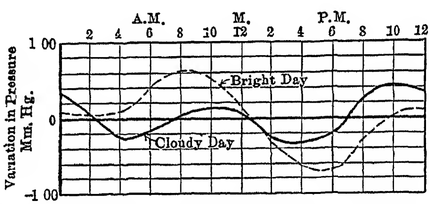


FIG. 16. — Effect of Clouds on Daily Variation in Barometric Pressure.

Synchronism of Various Phenomena. — It is an interesting fact, shown by Figs. 17 and 18, † that a number of solar and terrestrial phenomena show a similar variation. The interdependence of these phenomena is clearly shown by their synchronism.

The temperature variation at the surface of the earth shows a single diurnal wave. Above an altitude of about 400 meters, however, the temperature change assumes the semi-diurnal

* Hann, Dr. Julius, Lehrbuch der Meteorologie.

† Bigelow, Frank H., Atmospheric Circulation and Radiation, 1915.

wave form as shown in Fig. 19.* Above an elevation of about 2500 meters or one and one half miles both temperature and pressure remain substantially constant throughout the day. This fact is well shown by Figs. 19 and 20.*

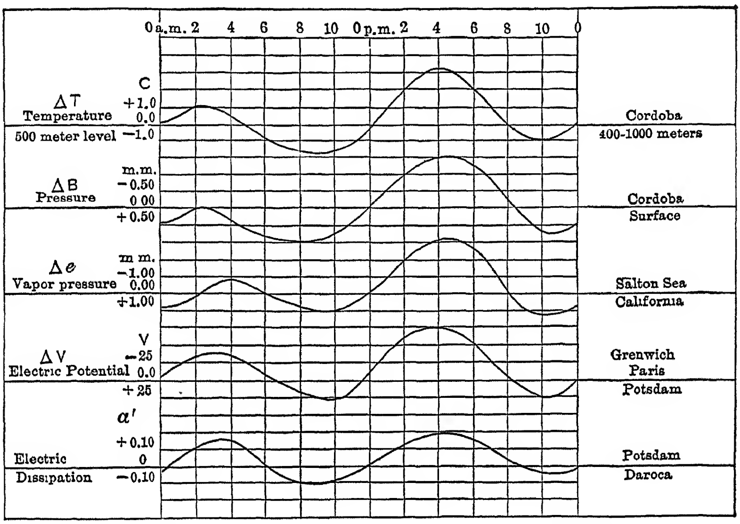


FIG. 17. — Synchronism of Various Phenomena (after Bigelow).

Greatly conflicting theories have been advanced regarding the cause of these semi-diurnal pressure waves. One explanation given for the occurrence of the early morning minimum is that it results from the formation of dew, the precipitation of some of the moisture in the air producing a reduction in barometric pressure. The latest explanation is that given by Professor Bigelow about as follows: The fundamental cause of the daily variation of barometric pressure is the diurnal convection. The rising air cools by expansion, and the falling air heats by compression, the former producing the afternoon wave and the latter the night wave to within 400 meters of the surface. At this elevation the more rapid cooling of the ground during the night makes itself felt, and there is radiation from the descending air to the ground.

* Bigelow, Frank H., Atmospheric Circulation and Radiation, 1915.

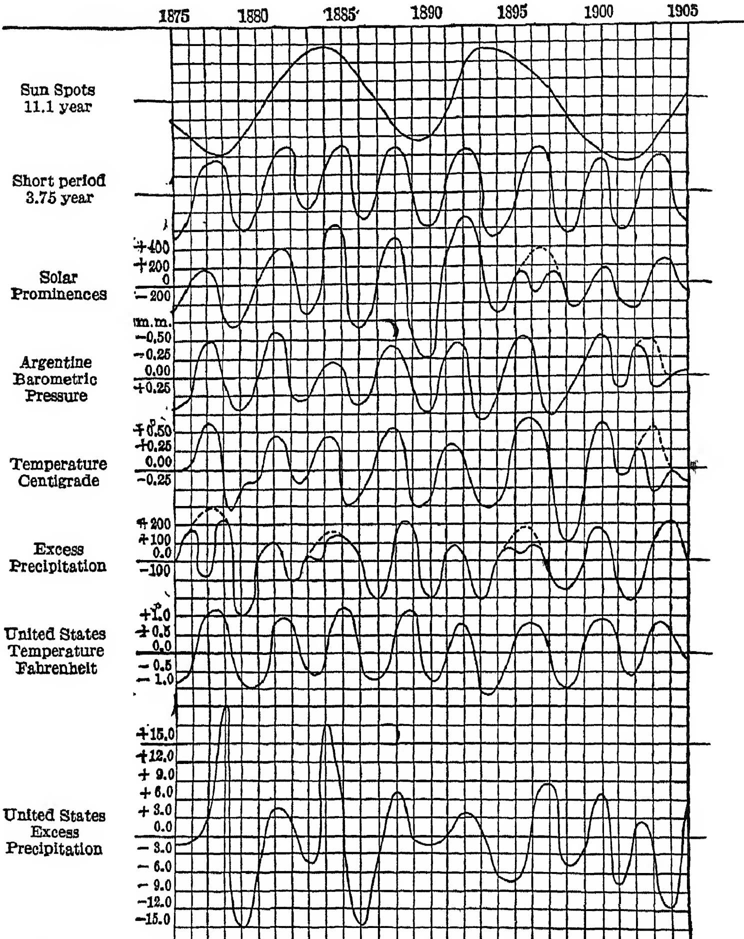


FIG. 18.—Variations in Solar and Terrestrial Phenomena (after Bigelow).

One of the most exhaustive studies of the correlation between solar and terrestrial phenomena is that made by A. Streiff and presented in Monthly Weather Review, July, 1926. The levels of certain lakes and the flow of streams are shown to follow cycles remarkably similar to various solar phenomena, when properly analyzed

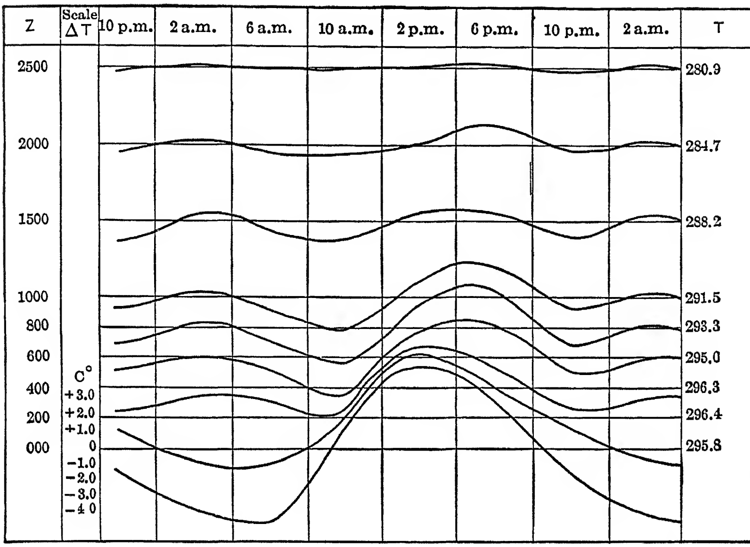


FIG. 19. — Diurnal Temperature Wave changing to Semi-diurnal Wave at Altitude of about 400 meters, and vanishing at Altitude of about 2500 meters (after Bigelow).

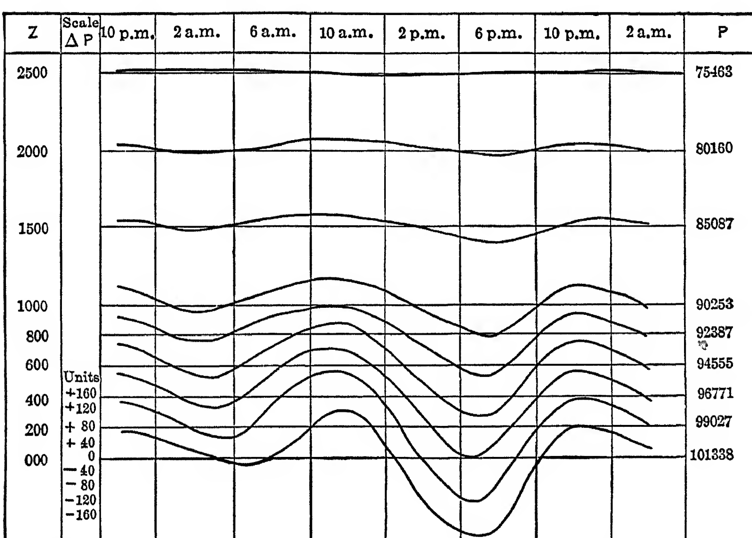


FIG. 20. — Semi-diurnal Pressure Wave vanishing at Altitude of about 2500 meters (after Bigelow).

Circulation of the Atmosphere

Wind Pressure. — Winds are important phenomena to the engineer, both from the viewpoint of the pressures produced on structures and of the excessive rates of rainfall made possible only through the circulation of the atmosphere.

Until the failure of the great steel bridge across the River Tay, in England, on December 28, 1879, the subject of wind stresses in structures had received little attention. Today the engineer who neglected at least to consider the possible effect of wind pressures in the design of a structure would be remiss in his duty. The values to assume for wind pressures and the determination of the resulting stresses, however, is no simple matter.

The wind pressure, in pounds per square foot, on a normal surface, is approximately equal to .004 times the square of the wind velocity in miles per hour, times the barometric pressure in inches mercury, divided by 30. A pressure of 50 lb. per square foot, for example, under normal barometric pressure, represents a wind velocity of about 112 miles per hour; 30 lb. per square foot represents a wind velocity of about 86 miles per hour. These wind pressures represent the highest pressures to be expected during "straight blows." "Twisters" — tornadoes — produce wind pressures against which it is impracticable to design. Wind velocities in tornadoes have been estimated at 300 to 500 miles per hour, with wind pressures of about 300 lb. per square foot. The sudden reductions in barometric pressure in a tornado cause great outward pressures on closed buildings, resulting in the blowing open of doors and windows, and other manifestations of explosive action.

The following table by Moore* gives the common name and significant facts regarding various wind velocities:

* Moore, W. L., Descriptive Meteorology, 1911.

Name	Velocity, miles per hour	Apparent effect
Calm.	0	No visible horizontal motion to inanimate matter.
Light.......	1 to 2	Causes smoke to move from the vertical.
Gentle... . .	3 5	Moves leaves of trees.
Fresh..	6 14	Moves small branches of trees and blows up dust.
Brisk .	15 24	Good sailing breeze and makes whitecaps.
High. ...	25 39	Sways trees and breaks small branches.
Gale . .	40 59	Dangerous for sailing vessels.
Storm. . .	60 79	Prostrates exposed trees and frail houses.
Hurricane	80 or more	Prostrates everything.

Cause of Winds. — The fundamental cause of the circulation of the atmosphere is the unequal heating of portions of the earth's surface. As the sun travels to the north of the equator during our summer, and again south during our winter, there is a shifting of the thermal equator. This and other factors result in some irregularities in the otherwise rather permanent and continual interchange of air between the warm equatorial regions and the cold polar regions. The land areas heat and cool more rapidly than the water areas in the same latitude. Differences in temperature between the equator and the poles result in north and south winds. Differences in temperature between the large land and water areas result in east and west winds. These larger, general wind movements are modified by the rotation of the earth, giving rise to certain fairly well-defined wind zones.

Wind Zones. — In the tropics there is a region of calms or doldrums, where the air movement is upward, resulting in almost daily heavy rainfall. On each side of this belt of equatorial calms there is a region in which the air moves toward the equator. Through the rotation of the earth, these air currents are deflected from true north and south winds into a westerly direction, and are known as the northeast trade winds in the northern hemisphere and the southeast trade winds in the southern hemisphere. In the upper air the currents, known as the counter, return or anti-trade winds, are in the opposite direction. At approximately latitude 30 degrees, north and south, the air currents are

downward, resulting in low humidity and light rainfall. These belts are known as the calms of Cancer and of Capricorn.

From latitudes 30 degrees toward the poles, covering most of the temperate and more densely populated portions of the earth's surface, there is the region of the prevailing westerlies, dominated by areas of low and high barometric pressure resulting from the unequal heating of the land and water masses. These low- and high-pressure areas follow each other across the continent at average velocities of 25 to 30 miles per hour, or 600 to 700 miles per day.

The winds accompanying these cyclonic movements are the only permanent winds with which we, in the United States, are concerned. They are the winds that determine our weather, our rainfall, our floods and our droughts.

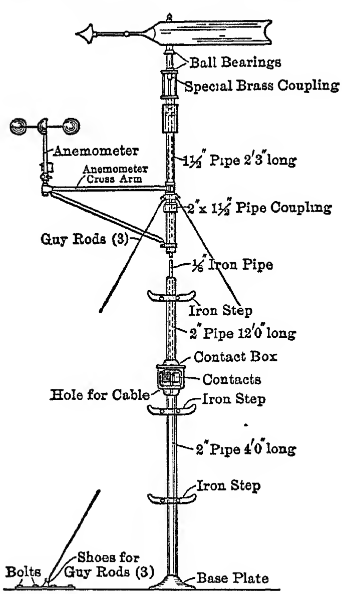


FIG. 21. — Wind Vane and Anemometer.

Periodic Winds. — In addition to the permanent general circulation above discussed, there are certain periodic winds which are of considerable importance over restricted areas. Among these are the monsoons, land and sea breezes, mountain and valley breezes.

Non-periodic. — In the region of the prevailing westerlies, cyclones and anti-cyclones are occasionally accompanied by high winds, such as the hurricane of the West Indies, the typhoon, the föhn, chinooks, blizzards and tornadoes.

Anemometers. — Wind velocity is measured by the United States Weather Bureau, mainly by Robinson cup anemometers, illustrated in Fig. 21. These instruments are so placed as to

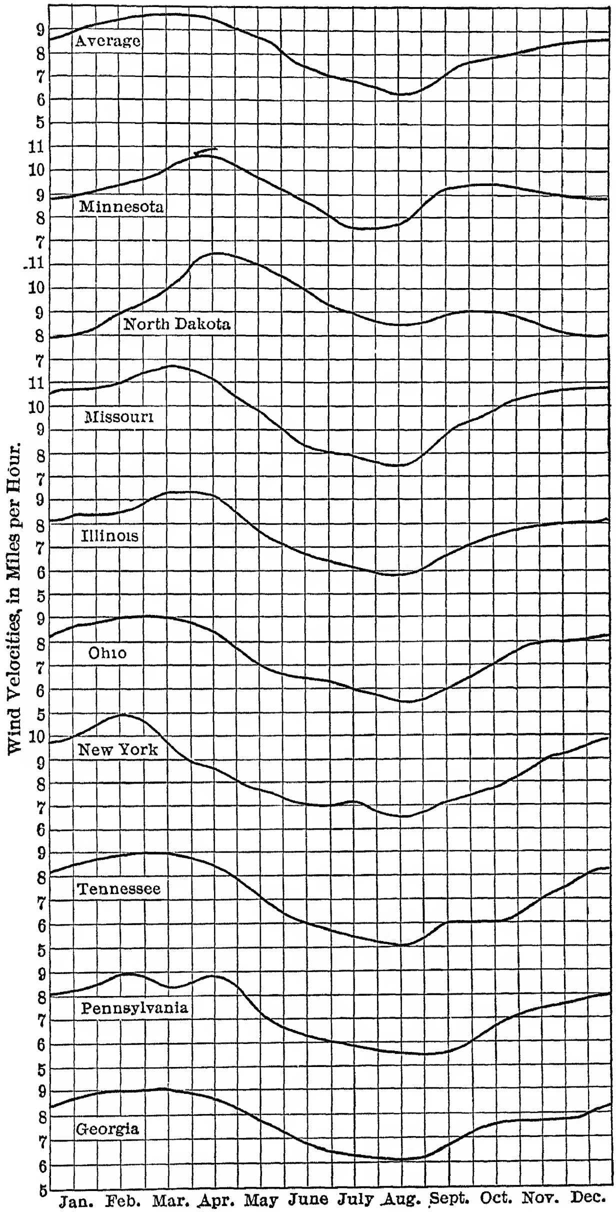


FIG. 22.—Monthly Mean Wind Velocities at Continental Stations in the United States.

record approximately the wind velocity at an elevation of about 30 feet above the general level of the surrounding country.

Mean Wind Velocities in the United States. — Fig. 22 gives the monthly mean wind velocity at typical stations in various parts of the United States. In the Northwest the highest average wind velocity occurs in the spring, at a time when the temperature is rising. This results in very high rates of evaporation immediately preceding and during the spring break-up, and accounts, in a measure, for the disappearance of the winter snowfall and the freedom from extreme floods experienced by the Northwestern States at times when all other conditions are favorable for high water.

CHAPTER III

WATER: ITS VARIOUS STATES AND THEIR PROPERTIES

Composition. — Water in the chemically pure state of the composition H_2O is not found in nature. As it occurs on the surface of the earth, water always contains more or less organic and inorganic material in solution and suspension. The importance to be attached to the impurities contained in water depends upon the contemplated use of the water. To be desirable for domestic purposes, water must be of a high standard of purity, not only as to chemical constituents, vegetable and animal matter carried, but also as to odor, color and taste. To be desirable for steam making, condensing and allied purposes, water should be reasonably free from sediment and incrustating materials. To be useful for power and navigation purposes, water may be of almost any degree of impurity, although the water of streams having their source in glaciers may contain sediment to an extent sufficient to make it unfit even for use in water-power development. In high-head projects provision must often be made for screening and sedimentation to prevent excessive wear on the water-wheels.

Physical Properties. — Perhaps the one most important physical property of water is its expansion upon freezing. Water increases in density until a temperature of 39.2° F. or 4° C. is reached, after which it slowly expands until at 32° F. or 0° C. upon solidifying, it expands about 10 per cent. After solidification, it again contracts, *i.e.*, increases in density, with decrease in temperature.

The effect of temperature and pressure on the state of water is shown in Fig. 23.

The water occurring in the earth's atmosphere as vapor in spring and fall when the night temperature reaches the freezing point cannot be under a pressure exceeding the maximum pressure of saturated vapor, which is .18 inch mercury at 32° F. Under such conditions water can pass directly from the vaporous state to the solid state resulting in the familiar phenomena of hoar frost and snow. Similarly, ice and snow at temperatures below freezing readily pass from the solid to the vaporous state.

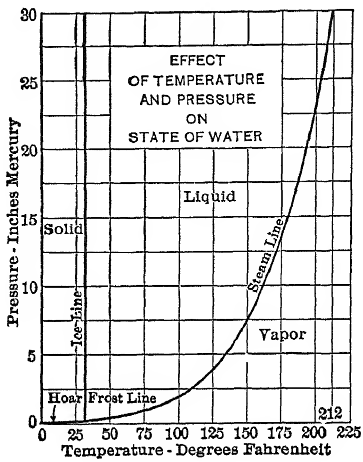


Fig. 23.

A body of water cooling down in the fall maintains a reasonably uniform temperature throughout until it is cooled down to 39.2° F. Upon further cooling, the cold water, being lighter, remains at the surface where cooling then proceeds rapidly until ice is formed. The liberation of latent heat during the formation of ice somewhat retards the further cooling. Ice at 32° F. being about 10 per cent lighter than water at the same temperature floats upon the surface and thickens with continued low temperatures, thus maintaining a temperature of substantially 39° F. in the entire body of water beneath the ice and preserving animal life.

If water is kept in a perfectly quiet condition, it can be cooled down to about 20° F. before ice forms. Upon freezing, however, the temperature immediately rises to 32° F. on account of the heat liberated in the process of congelation.

Frazil. — In flowing streams, where the velocity of the water is sufficient to prevent the formation of surface ice, "frazil" or "slush ice" will often be formed. Frazil consists of fine ice crystals, often several million to the cubic foot, that are carried along by the currents and, when present in large quantities, give

water a turbid appearance. Frazil forms most freely in flowing water on cold, cloudy days with an upstream wind. It never forms under ice cover, but the crystals are carried under the ice covering the quieter water, adhere to the sheet of ice above and accumulate at times until the entire channel is obstructed.

Anchor Ice. — On cold clear nights, when the radiation of heat from the surface of the earth is very rapid, ice needles known as "anchor ice," closely resembling frazil in appearance, form, particularly on dark-colored objects, on the beds of rather shallow, open bodies of water. Crystals of frazil floating in the water become entangled in the anchor ice formed on the bed of the stream and help to build up the mass. During the daytime the heat of the sun detaches anchor ice and brings it to the surface where it floats away, usually to become lodged under the ice cover of quieter water.

Anchor ice, and particularly frazil, often seriously obstruct canals and penstocks and require careful consideration in the design of works for the utilization of water in cold climates.

Elasticity. — The modulus of elasticity of water is approximately 295,000 lb. per square inch or $\frac{1}{100}$ that of steel, and it transmits sound and stress at the rate of substantially 4700 feet per second as against a rate of transmission of 1050 feet per second for air at 0° F.

Weight. — The weight of pure water at 39.2° F. is 62.4 lb. per cubic foot. At boiling temperatures, the weight has decreased to 59.7 lb. per cubic foot. Mineral spring waters weigh as high as 62.7 lb.; sea water 64 lb.; and the water of the Dead Sea and Great Salt Lake, Utah, weighs as much as 73 lb. per cubic foot. For ordinary computations, the weight of fresh surface waters may be taken as 62.5 lb. per cubic foot. This is substantially correct and is often a convenient figure because it represents just 1000 ounces avoirdupois.

Steam. — At temperatures of 100° C. or 212° F. under standard atmospheric pressure, water, upon the application of sufficient

heat, passes freely from the liquid to the gaseous state known as steam, with an increase in volume of 1658 times.

Specific Heat. — To raise the temperature of 1 gram of water 1° C. requires the application of one calorie unit of heat. Similarly, to raise 1 lb. of water 1° F. requires the application of 1 British thermal unit (B.t.u.) of heat. In other words, the heat required to raise the temperature of a unit volume of water 1 degree is really the measure of these heat units.

The heat required to raise the temperature of a given weight of water 1 degree would raise the temperature of the same weight of ice 2 degrees, of brick, or stone, about 5 degrees, and of iron or steel, about 9 degrees.

The tremendous capacity of water for storing heat energy is graphically shown in Fig. 24.

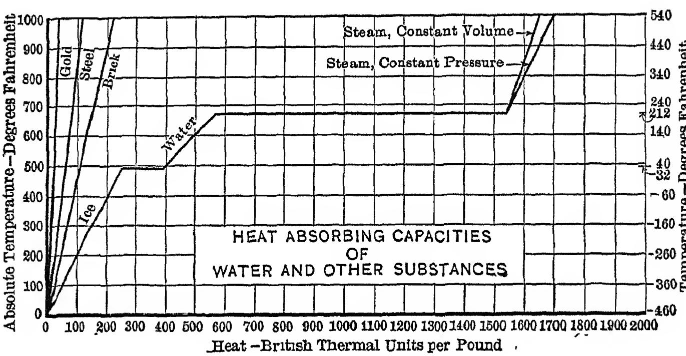


FIG. 24.

Heat of Vaporization. — To change one gram of water at ordinary boiling temperature into one gram of vapor, or steam, at the same temperature, requires the expenditure of 536 calories of heat. To effect the same change in 1 lb. of water requires 970 B.t.u.

Heat of Fusion. — When 1 gram of water changes from the liquid state at 0° C. to the solid state, 80 calories of heat are liberated; similarly, when 1 lb. of water changes to ice, 144 B.t.u. are liberated. The heat so liberated warms the water and thus tends to reduce the amount of freezing.

The Vapor of Water and Its Condensation

Characteristics of Water Vapor. — Water in the gaseous state has a specific gravity of .622 as compared with dry air and conforms approximately, though not exactly, to Boyle's law, which states that if the temperature of a gas is kept constant, the product of its pressure times its volume also remains constant. Water vapor also roughly obeys Charles' or Gay-Lussac's law, which states that if the volume of a gas is kept constant, the pressure which it exerts against the walls of its container decreases in direct proportion to the change in temperature measured from what is known as "absolute zero," *i.e.*, a temperature of 273 degrees below zero, Centigrade, at which all molecular motion is believed to cease. As water does not turn freely into the gaseous state at temperatures below 100° C., under normal barometric pressure, whereas the other gases of the atmosphere vaporize freely at temperatures far below those of the coldest outside air, it might be expected that the nearly saturated vapor of water would, in its behavior, deviate somewhat from Boyle's and Charles' laws.

Vapor Pressure. — If a drop of water, so small as to be scarcely visible, were introduced into the vacuum over the mercury of a barometer at a temperature of, say, 80° F., the water would turn into vapor and depress the mercury column about 1 inch. The further addition of small globules of water would not result in further vaporization or further depression of the mercury column except for the scarcely perceptible volume of the liquid added. Now, the actual weight of the added globule of water was negligible, especially when compared with a liquid 13.6 times as heavy, yet it depressed the column of mercury about an inch, *i.e.*, it exerted a *pressure* on the top of the mercury column equal to a depth of over 1 foot of water. This pressure which the water in its gaseous state exerts is variously called "vapor pressure," "vapor tension," "elastic pressure" and "gaseous pressure." It is the same kind of pressure as that exerted by steam in the

cylinders of an engine. This vapor pressure or gaseous pressure is a function of the temperature.

If, now, the temperature of the water on top of the mercury is raised to 100° F., more of the water will vaporize and the mercury column will be depressed about 2 inches. If the temperature is raised to 150° F. the mercury column will be depressed about 7.5 inches and if the temperature is raised to slightly above 212° F. the mercury column will be depressed the full 30 inches, *i.e.*, the vapor pressure of the water will be exactly equal to the pressure of the atmosphere and the liquid will " boil " — vaporize freely — until it has all changed its state.

If, instead of heating the water over the mercury column, we had lifted the barometer tube partly out of its cup so as to increase the space above the column of mercury, some water would have vaporized, but the *height* of the mercury column above the surface of the mercury in the cup would have remained the same, until saturation.

Distribution of Water Vapor. — In the free air of the earth the water vapor exists in an almost saturated form, and its distribution is dependent mainly upon temperature and convection currents. The elastic pressure of water vapor is a reasonably accurate measure of the weight of a unit volume of vapor, but it is not, by any means, a measure of the weight, on a unit area, of the entire column of vapor above that area.

Relation of Vapor Pressure to Weight of Vapor. — If water vapor followed Boyle's law exactly, the weight of vapor in a given volume would be directly proportional to the elastic pressure exerted by the vapor at the same temperature. According to Marvin: *

$$\begin{array}{c}\text{Weight of vapor in grains}\\ \text{per cu. ft.} = 11.7449\end{array} \left\{ \frac{\text{vapor pressure in inches mercury}}{\left(1 + .002037 \left\{ \begin{array}{c}\text{temperature in}\\ \text{degrees F.} - 32\end{array} \right\}\right)} \right\}.$$

* Marvin, C. F., Professor of Meteorology, U. S. Weather Bureau, in "Psychrometric Tables," 1912.

Table 2 gives the weight of a cubic foot of water vapor at different temperatures and percentages of saturation.

Change in Vapor Pressure with Temperature. — Table 3 gives the elastic pressure, in inches mercury, as determined experimentally by Regnault and Marvin, of saturated vapor at various temperatures. Values below 32 degrees differ substantially from those given by Broch. Above 32 degrees, Broch's and Marvin's values are identical.

TABLE 2.—WEIGHT OF A CUBIC FOOT OF AQUEOUS VAPOR AT DIFFERENT TEMPERATURES AND PERCENTAGES OF SATURATION

(U. S. Weather Bureau)

Temp., °F.	Percentage of saturation									
	10	20	30	40	50	60	70	80	90	100
	grains	grains	grains	grains	grains	grains	grains	grains	grains	grains
−20	0 017	0 033	0 050	0 066	0 083	0 100	0 116	0 133	0 149	0 166
−19	0 017	0 035	0 052	0 070	0 087	0 104	0 122	0 139	0 157	0 174
−18	0 018	0 037	0 055	0 074	0 092	0 110	0 129	0 147	0 166	0 184
−17	0 020	0 039	0 059	0.078	0 098	0 118	0 137	0 157	0 176	0 196
−16	0 021	0 041	0 062	0.083	0.104	0.124	0.145	0 166	0 186	0 207
−15	0 022	0 044	0 065	0 087	0 109	0 131	0 153	0 174	0 196	0 218
−14	0 023	0 046	0 069	0 092	0 116	0 139	0 162	0 185	0 208	0 231
−13	0 024	0 049	0 073	0 097	0 122	0 146	0 170	0 194	0 219	0 243
−12	0 026	0 051	0 077	0 103	0 128	0 154	0 180	0 206	0.231	0 257
−11	0 027	0 054	0 081	0 108	0 135	0 162	0 189	0.216	0 243	0 270
−10	0 028	0 057	0 086	0 114	0 142	0 171	0 200	0 228	0 256	0 285
− 9	0 030	0 060	0 090	0 120	0 150	0 180	0 210	0 240	0 270	0 300
− 8	0 032	0 063	0 095	0 126	0 158	0 190	0 221	0 253	0 284	0 316
− 7	0 033	0 066	0 100	0 133	0 166	0 199	0 232	0 266	0 299	0 332
− 6	0 035	0 070	0 105	0 140	0 175	0 210	0 245	0 280	0 315	0 350
− 5	0 037	0 074	0 111	0 148	0 185	0 222	0 259	0 296	0 333	0 370
− 4	0 039	0 078	0 117	0 156	0 194	0 233	0 272	0 311	0 350	0 389
− 3	0 041	0 082	0 123	0 164	0 206	0 247	0 288	0 329	0.370	0 411
− 2	0 043	0 087	0 130	0 174	0 217	0 260	0 304	0 347	0 391	0 434
− 1	0 046	0 091	0 137	0 183	0 228	0 274	0 320	0 366	0 411	0.457
0	0 048	0 096	0 144	0 192	0 240	0 289	0 337	0 385	0 433	0 481
+ 1	0 050	0 101	0 152	0 202	0 252	0 303	0 354	0 404	0 454	0 505
2	0 053	0 106	0 159	0 212	0 264	0 317	0 370	0 423	0 476	0 529
3	0.055	0 111	0 166	0 222	0 277	0 332	0 388	0 443	0 499	0.554
4	0 058	0 116	0 175	0 233	0 291	0 349	0 407	0 466	0 524	0.582
5	0 061	0 122	0 183	0 244	0 305	0 366	0 427	0 488	0 549	0 610
6	0 064	0 128	0 192	0 256	0 320	0 383	0 447	0 511	0 575	0 639
7	0 067	0 134	0 201	0 268	0 336	0 403	0 470	0 537	0 604	0.671
8	0 070	0 141	0 211	0 282	0 352	0 422	0 493	0 563	0 634	0.704
9	0 074	0 148	0 222	0 296	0 370	0 443	0 517	0 591	0 665	0.739
10	0 078	0 155	0 233	0 310	0 388	0 466	0 543	0 621	0 698	0 776
11	0 082	0 163	0 245	0 326	0 408	0 490	0 571	0 653	0 734	0.816
12	0 086	0 171	0 257	0.342	0 428	0 514	0 599	0.685	0.770	0.856
13	0 090	0 180	0 269	0 359	0 449	0 539	0 629	0 718	0 808	0.898
14	0 094	0.188	0 282	0 376	0 470	0 565	0 659	0 753	0 847	0.941
15	0 099	0 197	0 296	0 394	0 493	0 592	0 690	0 789	0 887	0.986
16	0 103	0 206	0 310	0 413	0 516	0 619	0 722	0 826	0 929	1 032
17	0 108	0 216	0 324	0 432	0 540	0 648	0 756	0 864	0.972	1 080
18	0 113	0 226	0.338	0 451	0 564	0 677	0 790	0 902	1 015	1.128
19	0 118	0.236	0.354	0.472	0 590	0 709	0 827	0 945	1.063	1 181
20	0 124	0 247	0 370	0 494	0 618	0 741	0 864	0 988	1 112	1 235
21	0 129	0 259	0 388	0 518	0 647	0 776	0 906	1 035	1 165	1.294
22	0 136	0 271	0 406	0 542	0 678	0 813	0 948	1 084	1 220	1 355
23	0 142	0 284	0.425	0 567	0 709	0 851	0 993	1 134	1 276	1 418
24	0.148	0.297	0.445	0 593	0 742	0 890	1 038	1 186	1 335	1 483
25	0 155	0 310	0 465	0 620	0 776	0 931	1 086	1 241	1 396	1 551
26	0 162	0 325	0 487	0 649	0 812	0 974	1 136	1 298	1.461	1 623
27	0 170	0 339	0.509	0 679	0 848	1 018	1 188	1 358	1 527	1 697
28	0 177	0 355	0 532	0 709	0 886	1 064	1 241	1.418	1 596	1 773
29	0 185	0 371	0 556	0 741	0 926	1.112	1 297	1 482	1 668	1 853
30	0 194	0 387	0 580	0 774	0.968	1 161	1 354	1 548	1.742	1 935
31	0 202	0 404	0 607	0 809	1 011	1 213	1 415	1 618	1 820	2 022
32	0 211	0 422	0 634	0 845	1 056	1.268	1 479	1.690	1 902	2 113
33	0 219	0 439	0 658	0 878	1.097	1 316	1 536	1 755	1 975	2 194
34	0 228	0.456	0 684	0 912	1 140	1 367	1 595	1 823	2.051	2.279
35	0 237	0.473	0.710	0.946	1.183	1 420	1 656	1 893	2 129	2 366
36	0 246	0 491	0.737	0 983	1,228	1 474	1.720	1 966	2 211	2.457
37	0 255	0 510	0.765	1 020	1 275	1 530	1.785	2.040	2 295	2.550
38	0 265	0 529	0.794	1 058	1.323	1 588	1.852	2 117	2.381	2.646
39	0.275	0.549	0 824	1 098	1.373	1 648	1.922	2 197	2 471	2 746
40	0 285	0 570	0 855	1.140	1 424	1.709	1.994	2 279	2.564	2 849
41	0 296	0 591	0.886	1 182	1 478	1.773	2 068	2.364	2.660	2.955
42	0 306	0.613	0 919	1 226	1 532	1 838	2.145	2.451	2.758	3.064
43	0 318	0.635	0.953	1 271	1 588	1 906	2.224	2 542	2.859	3.177
44	0 329	0.659	0.988	1 318	1 647	1 976	2.306	2 635	2.965	3.294

TABLE 2.—WEIGHT OF A CUBIC FOOT OF AQUEOUS VAPOR AT DIFFERENT TEMPERATURES AND PERCENTAGES OF SATURATION.—*Continued*

(U. S. Weather Bureau)

Temp., ° F.	Percentage of saturation									
	10	20	30	40	50	60	70	80	90	100
	grains	grains	grains	grains	grains	grains	grains	grains	grains	grains
45	0 341	0 683	1 024	1 366	1.707	2 048	2 390	2 731	3 073	3 414
46	0 354	0 708	1 062	1 416	1 770	2 123	2 477	2 831	3 185	3 539
47	0 367	0 733	1 100	1 467	1 834	2 200	2 567	2 934	3 300	3 667
48	0 380	0 760	1 140	1 520	1 900	2 280	2 660	3 040	3 420	3 800
49	0 394	0 787	1 181	1 574	1 968	2 362	2 755	3.149	3 542	3.936
50	0 408	0 815	1 223	1 630	2 038	2 446	2 853	3 261	3 668	4 076
51	0 422	0 844	1 267	1 689	2 111	2 533	2 955	3 378	3 800	4 222
52	0 437	0 874	1 312	1 749	2 186	2 623	3 060	3 498	3 935	4 372
53	0 453	0 905	1 358	1 810	2 263	2 716	3 168	3 621	4 073	4 526
54	0 468	0 937	1 406	1 874	2 342	2 811	3 280	3 748	4 216	4 685
55	0 485	0 970	1 455	1 940	2 424	2 909	3 394	3 879	4 364	4 849
56	0 502	1 003	1 505	2 006	2 508	3 010	3 511	4 013	4 514	5 016
57	0 519	1 038	1 557	2 076	2 596	3 115	3 634	4 153	4 672	5 191
58	0 537	1 074	1 611	2 148	2 685	3 222	3 759	4 296	4 833	5 370
59	0 556	1 111	1 666	2 222	2 778	3 333	3 888	4 444	5 000	5 555
60	0 574	1 149	1 724	2 298	2 872	3 447	4 022	4 596	5 170	5.745
61	0 594	1 188	1 782	2 376	2 970	3 565	4 159	4 753	5 347	5 941
62	0 614	1 228	1 843	2 457	3 071	3 685	4 299	4 914	5 528	6 142
63	0 635	1 270	1 905	2 540	3 174	3 809	4 444	5 079	5 714	6 349
64	0 656	1 313	1 969	2 625	3 282	3 938	4 594	5 250	5 907	6.563
65	0 678	1 356	2 035	2 713	3 391	4 069	4 747	5 426	6 104	6.782
66	0 701	1 402	2 103	2 804	3 504	4 205	4 906	5 607	6 308	7 009
67	0 724	1 448	2 172	2 896	3 620	4 345	5 069	5 793	6 517	7 241
68	0 748	1 496	2 244	2 992	3 740	4 488	5 236	5 984	6 732	7 480
69	0 773	1 545	2 318	3 090	3 863	4.636	5 408	6 181	6 953	7.726
70	0 798	1 596	2 394	3 192	3 990	4 788	5 586	6 384	7 182	7.980
71	0 824	1 648	2 472	3 296	4 120	4 944	5 768	6 592	7 416	8 240
72	0 851	1 702	2 552	3 403	4 254	5 105	5 956	6 806	7 657	8 508
73	0 878	1 756	2 635	3 513	4 391	5 269	6 147	7 026	7 904	8 782
74	0 907	1.813	2 720	3 626	4 533	5 440	6 346	7 253	8 159	9.066
75	0 936	1 871	2 807	3 742	4 678	5 614	6 549	7 485	8 420	9 356
76	0 966	1 931	2 896	3 862	4 828	5 793	6 758	7 724	8 690	9 655
77	0 996	1 992	2 989	3 985	4.981	5 977	6 973	7 970	8 966	9 962
78	1 028	2 055	3 083	4 111	5 138	6 166	7 194	8 222	9 249	10 277
79	1 060	2 120	3 180	4.240	5 300	6 361	7 421	8 481	9 541	10 601
80	1 093	2 187	3 280	4 374	5.467	6 560	7 654	8 747	9 841	10 934
81	1.128	2 255	3 382	4 510	5 638	6 765	7 892	9 020	10 148	11 275
82	1 163	2 325	3 488	4 650	5 813	6.976	8 138	9 301	10 463	11 626
83	1 199	2 397	3 596	4 795	5 994	7 192	8 391	9 590	10 788	11 987
84	1 236	2 471	3 707	4 942	6 178	7.414	8.649	9 885	11.120	12.356
85	1 274	2 547	3 821	5 094	6 368	7 642	8 915	10 189	11 462	12 736
86	1 313	2 625	3 938	5 251	6 564	7 877	9 189	10 502	11 814	13 127
87	1 353	2 705	4 058	5 410	6 763	8 116	9 468	10 821	12 173	13 526
88	1.394	2.787	4 181	5.575	6.968	8 362	9 756	11 150	12.543	13 937
89	1 436	2.872	4 308	5 744	7.180	8.615	10 051	11 487	12 923	14.359
90	1 479	2 958	4 437	5 916	7 395	8 874	10 353	11 832	13 311	14 790
91	1 523	3.047	4.570	6 094	7.617	9 140	10 664	12 187	13 711	15 234
92	1 569	3 138	4 707	6 276	7 844	9 413	10.982	12 551	14 120	15.689
93	1 616	3 231	4 846	6 462	8 078	9 693	11 308	12.924	14 540	16 155
94	1.663	3 327	4 990	6 654	8 317	9.980	11.644	13 307	14 971	16.634
95	1.712	3 425	5 137	6 850	8 562	10.274	11.987	13.699	15 412	17 124
96	1 763	3.525	5 288	7 050	8.813	10 576	12.338	14.101	15 863	17 626
97	1.814	3.628	5 443	7 257	9.071	10 885	12.699	14.514	16 328	18 142
98	1.867	3.734	5.601	7.468	9.336	11.203	13.070	14.937	16 804	18 671
99	1.921	3.842	5 764	7 685	9.606	11.527	13.448	15 370	17 291	19.212
100	1 977	3.953	5.930	7.906	9.883	11.860	13 836	15 813	17.789	19.766
101	2.034	4 067	6.100	8 134	10.168	12 201	14 234	16.268	18 302	20 335
102	2 092	4 183	6.275	8 367	10.458	12.550	14 642	16.734	18.825	20.917
103	2 151	4 303	6.454	8.606	10.757	12.908	15 060	17.211	19.363	21.514
104	2.212	4.425	6.638	8.850	11.062	13.275	15.488	17.700	19.912	22 125
105	2.275	4 550	6 825	9.100	11.375	13.650	15.925	18.200	20.475	22.750
106	2 339	4.678	7 018	9.357	11.696	14.035	16.374	18.714	21.053	23 392
107	2.405	4.809	7 214	9.619	12.024	14 429	16.834	19.238	21.643	24 048
108	2 472	4.944	7.416	9 888	12.360	14 832	17.304	19.776	22 248	24 720
109	2.541	5 082	7.622	10.163	12 704	15 245	17.786	20.326	22 867	25 408
110	2.611	5.222	7.834	10.445	13.056	15 667	18.278	20.890	23.501	26.112

TABLE 3.—ELASTIC PRESSURE OF SATURATED WATER VAPOR AT DIFFERENT TEMPERATURES

(U. S. Weather Bureau)

Air temp., ° F.	Vapor press., in. Hg.	Air temp., ° F.	Vapor press., in. Hg.	Air temp., ° F.	Vapor press., in. Hg.	Air temp., ° F.	Vapor press., in. Hg.
−40	0 0039	5	0.0491	50	0.360	95	1.645
−39	41	6	0 0515	51	0 373	96	1.696
−38	44	7	0 0542	52	0 387	97	1 749
−37	46	8	0.0570	53	0 402	98	1 803
−36	48	9	0.0600	54	0 417	99	1.859
−35	0 0051	10	0 0631	55	0 432	100	1.916
−34	54	11	0 0665	56	0 448	101	1.975
−33	57	12	0 0699	57	0 465	102	2 035
−32	61	13	0 0735	58	0 482	103	2 097
−31	65	14	0.0772	59	0 499	104	2.160
−30	0 0069	15	0.0810	60	0 517	105	2.225
−29	74	16	0.0850	61	0.536	106	2.292
−28	78	17	0.0891	62	0.555	107	2 360
−27	83	18	0.0933	63	0 575	108	2.431
−26	89	19	0 0979	64	0 595	109	2 503
−25	0 0094	20	0 103	65	0 616	110	2.576
−24	0.0100	21	0 108	66	0 638	111	2 652
−23	106	22	0 113	67	0.661	112	2.730
−22	112	23	0 118	68	0 684	113	2 810
−21	119	24	0 124	69	0.707	114	2 891
−20	0.0126	25	0.130	70	0.732	115	2 975
−19	133	26	0.136	71	0.757	116	3.061
−18	141	27	0.143	72	0.783	117	3.148
−17	150	28	0 150	73	0.810	118	3 239
−16	159	29	0.157	74	0.838	119	3.331
−15	0.0168	30	0.164	75	0 866	120	3 425
−14	178	31	0.172	76	0.896	121	3.522
−13	188	32	0.180	77	0 926	122	3.621
−12	199	33	0.187	78	0.957	123	3.723
−11	210	34	0.195	79	0 989	124	3.827
−10	0 0222	35	0.203	80	1.022	125	3.933
− 9	234	36	0.211	81	1.056	126	4.042
− 8	247	37	0.219	82	1.091	127	4 154
− 7	260	38	0.228	83	1.127	128	4 268
− 6	275	39	0 237	84	1.163	129	4.385
− 5	0 0291	40	0.247	85	1.201	130	4 504
− 4	307	41	0.256	86	1.241	131	4 627
− 3	325	42	0.266	87	1.281	132	4.752
− 2	344	43	0.277	88	1.322	133	4.880
− 1	363	44	0.287	89	1.364	134	5 011
0	0.0383	45	0.298	90	1.408	135	5.145
+ 1	403	46	0.310	91	1.453	136	5.282
2	423	47	0.322	92	1.499	137	5.422
3	444	48	0 334	93	1.546	138	5.565
4	467	49	0 347	94	1.595	139	5.712

At 0° F. the vapor pressure is doubled for an increase of 13 degrees in temperature. At 50 degrees it is doubled for an increase of 19 degrees, and at 100° F., the maximum vapor pressure is doubled for an increase of 23 degrees in temperature. At ordinary open-air temperatures, then, the elastic pressure of saturated water vapor is substantially doubled for every 20° F. increase in temperature.

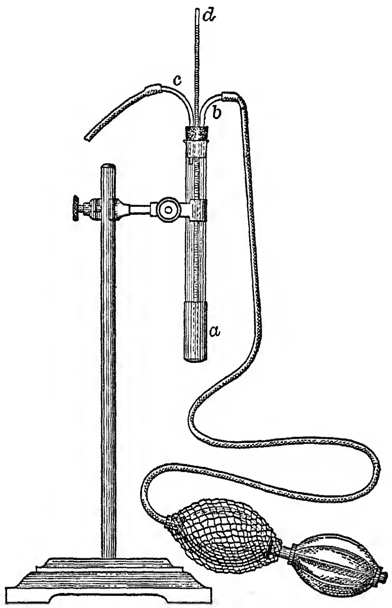


FIG. 25. — Typical Dew-point Apparatus.

The amount of water vapor in the atmosphere may be determined directly with some form of dew-point apparatus, or indirectly by means of wet- and dry-bulb thermometers, or by means of substances such as hair, wool, etc., which are sensitive to moisture.

Dew-point Hygrometers.— All direct hygrometers utilize the principle that at a given temperature and pressure only a certain definite amount of water vapor can occupy a given space, and that as soon as the space is saturated with moisture, dew will be deposited.

Fig. 25 shows a typical dew-point apparatus. It consists essentially of:

a. A thin polished silver cup, cemented upon the lower end of a glass tube, and filled with some volatile liquid, such as sulphuric ether.

b. A long tube joined to a rubber aspirator and extending through the stopper in the upper end of the glass tube to below the surface of the volatile liquid.

c. A tube extending a short distance through the stopper,

and serving to carry off the fumes generated in the apparatus.

d. A delicate thermometer extending through the stopper in the glass tube, and having its bulb immersed in the liquid.

By means of the aspirator, air is forced through the tube (*b*) causing it to bubble up through the ether, vaporizing some of the ether, and, consequently, cooling the silver cup. The outside air coming in contact with the silver cup is cooled to the same temperature. When this temperature is sufficiently low so that the vapor in the outside air is condensed to the point of saturation, dew is deposited on the outside of the silver cup. The maximum vapor pressure which corresponds to the temperature at which dew will just deposit on the silver cup, represents the actual vapor pressure in the air at the time. The observer must refrain from breathing on the apparatus, but the air may advantageously be given a very gentle motion by light fanning.

Indirect hygrometers consist of wet- and dry-bulb thermometers, and of instruments depending for their action on substances such as hair, wool and certain mineral salts, which are sensitive to moisture. Hygrometers of the latter class do not give very accurate results, and need frequent comparison with wet- and dry-bulb hygrometers to make their readings of much value. Good hair hygrometers are the best instruments in this class.

Wet- and Dry-bulb Hygrometers. — Indirect hygrometers, or psychrometers, utilizing wet- and dry-bulb thermometers in the determination of vapor pressure, depend upon the principle that evaporation results in cooling. The wet-bulb thermometer is wrapped with a silk or muslin wick, one end of which is immersed in distilled water. When air containing unsaturated vapor flows past the moist wick surrounding the wet-bulb thermometer, it absorbs some of the water in vapor form. The transformation of the water from the liquid to the vaporous state consumes heat, resulting in a reduction in the temperature of the moist wick, and its enclosed thermometer.

By comparison of the depression of the temperature of the wet-bulb thermometer for given readings of the dry-bulb thermometer and a given barometric pressure, with simultaneous determinations of the temperature of the dew-point, by means of a dew-point apparatus, and a consideration of the fundamental principles underlying the action of the wet- and dry-bulb thermometers, formulas have been derived and tables prepared from which the relative humidity, or the vapor pressure, may be read directly for a given depression of the wet-bulb thermometer and a given reading of the dry-bulb thermometer.

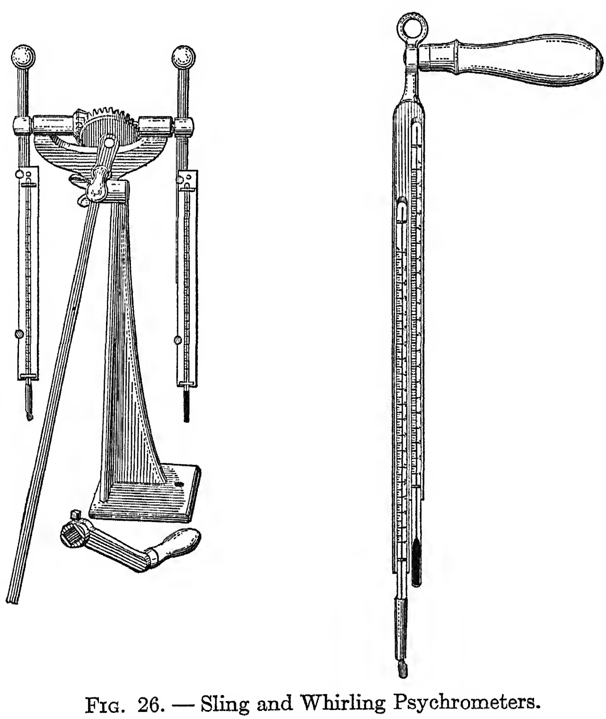


Fig. 26. — Sling and Whirling Psychrometers.

Stationary wet- and dry-bulb thermometers are frequently used indoors but do not give accurate results unless vigorously fanned before reading. Sling or whirling psychrometers are regularly used outdoors in the shelters at the telegraphic reporting stations of the United States Weather Bureau at which

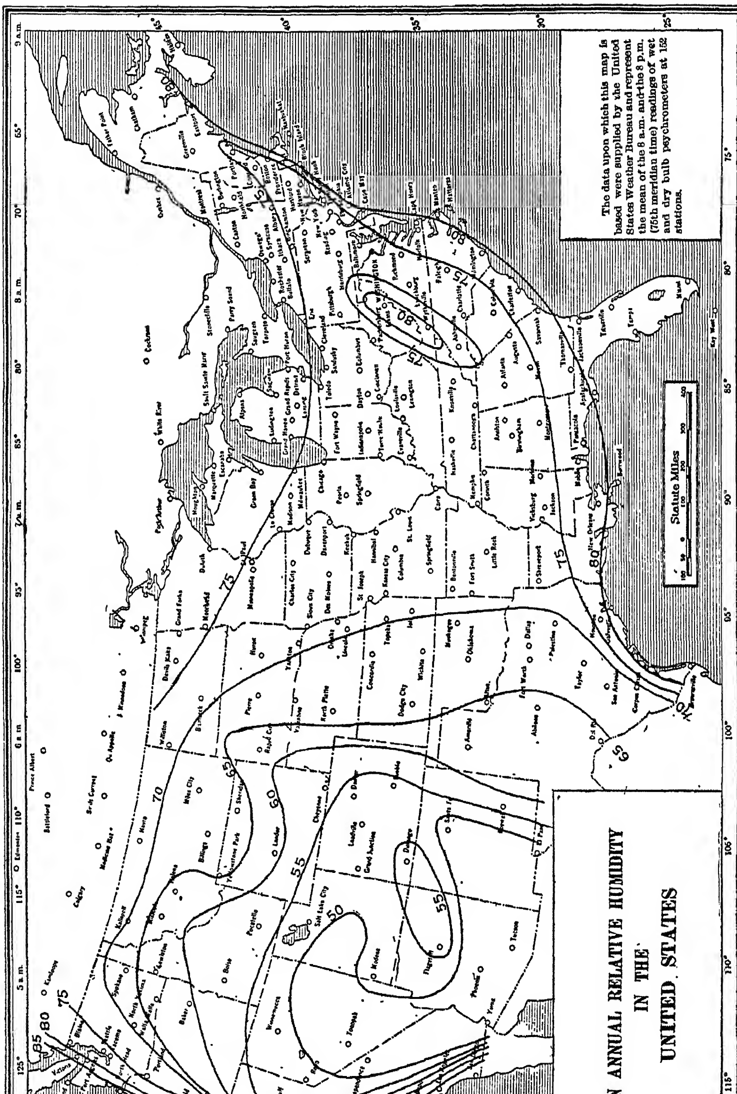

MEAN ANNUAL RELATIVE HUMIDITY
IN THE
UNITED STATES
The data upon which this map is based were supplied by the United States Weather Bureau and represent the mean of the 8 a.m. and the 8 p.m. (75th meridian time) readings of wet and dry bulb psychrometers at 152 stations.
Statute Miles

FIG. 27.

twice-a-day determinations of relative humidity are regularly made.

Humidity. — Fig. 26 shows typical sling and whirling psychrometers. The ratio of the actual vapor pressure to the maximum pressure of saturated vapor at the given air temperature constitutes the "relative humidity." The actual weight of water vapor per unit of volume is usually designated the "absolute humidity."

Both relative and absolute humidity show considerable variation with the seasons and in different localities, depending primarily upon the temperature and the moisture supply. The average relative humidity for the entire earth's surface is about 80 per cent. The mean annual relative humidity in the United States is shown in Fig. 27. High relative humidity is found along the seashore, and low relative humidity in the region east of the Rocky Mountains.

Changes in relative humidity with season are graphically shown in Figs. 28 and 29. In general, the higher the temperature the lower the relative humidity, because of a prevailing deficiency in the supply of moisture.

Figs. 30 to 38 show typical daily changes in air temperature, relative humidity and actual vapor pressure in Minnesota, in California and in the Panama Canal zone.

A synopsis of weather conditions accompanies the graphs to permit of an intelligent study and interpretation of the data.

Knowing the actual vapor pressure, the temperature of the dew-point can be readily determined. This temperature is of considerable importance, because it is substantially the limit to which the temperature of the night air may fall, because of the fact that the heat liberated when dew is deposited tends to prevent the temperature from falling below that of the dew-point.

Fig. 14, p. 28, gives a typical graph of the variation in relative humidity with altitude up to an elevation of 10 miles.

Density of Air. — The total weight of the air at sea level, as previously stated, is equivalent to the weight of 29.9 inches of

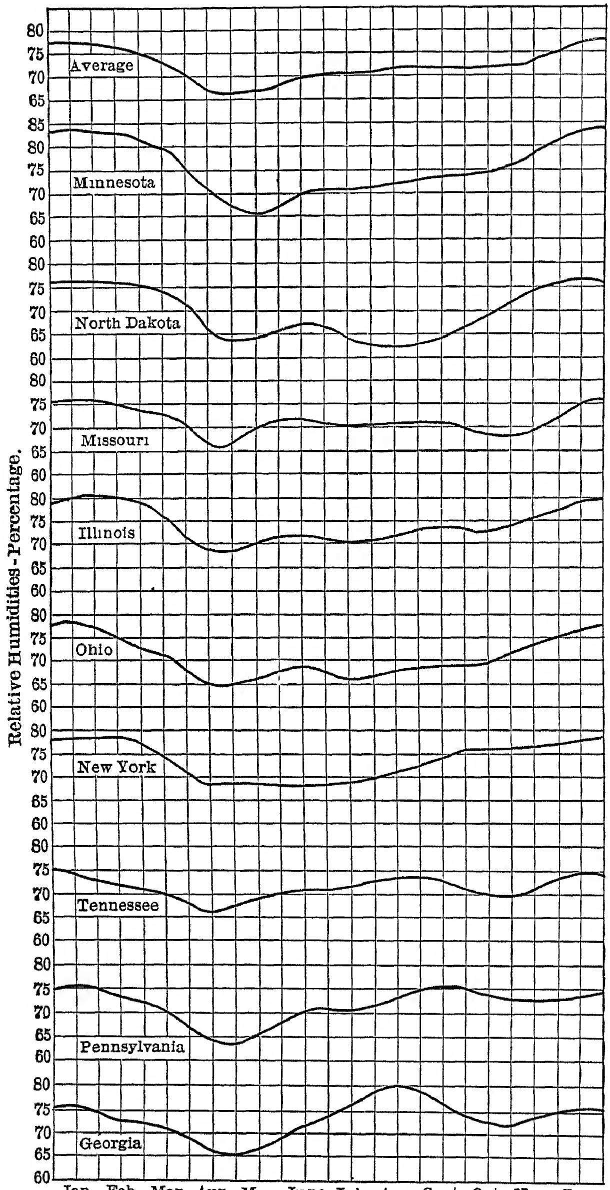


FIG. 28. — Monthly Mean Relative Humidities at Continental Stations in the United States.

mercury or 33.8 feet of water. The weight of a unit volume of air at sea level elevation and 0° C. is .00129278 times the weight of an equal volume of water. If the entire atmosphere, then, were of the same density as the air at sea level, the total depth

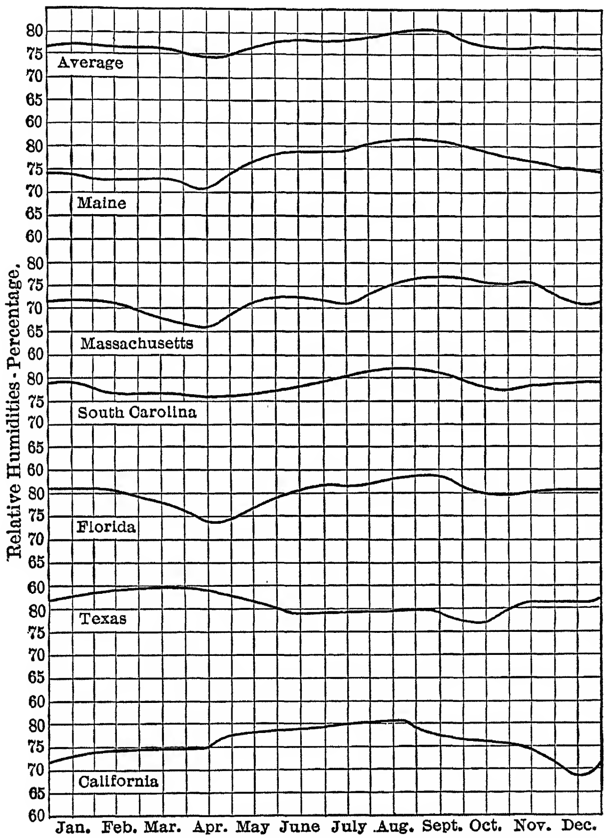


FIG. 29. — Monthly Mean Relative Humidities at Coastal Stations in the United States.

of air covering the earth would be about 26,200 feet. On account of the elasticity and compressibility of the gases, however, the density decreases with altitude and the atmosphere extends to a much greater height than 5 miles. In a homogeneous atmosphere

of uniform density, the reduction in pressure would be in direct proportion to the increase in altitude. In the atmosphere of the earth the reduction in pressure becomes continually less for every succeeding uniform increase in altitude. This fact is illustrated in Fig. 14, p. 28.

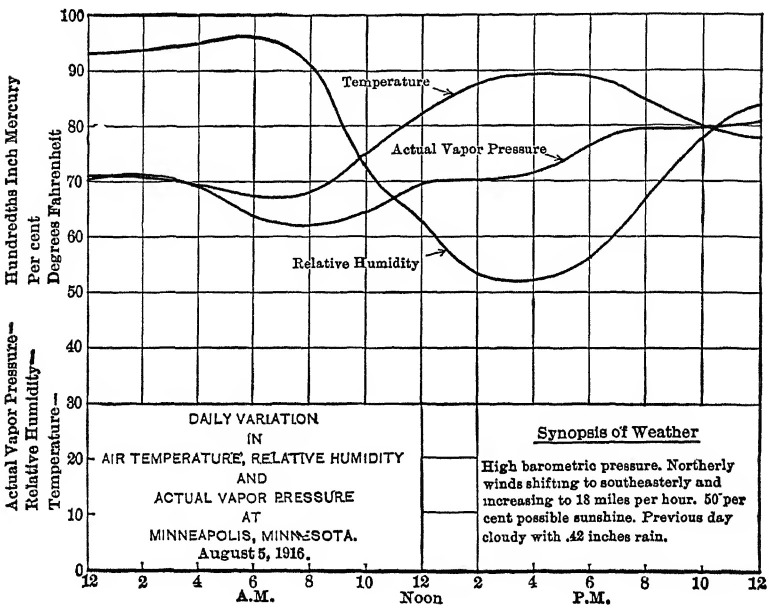
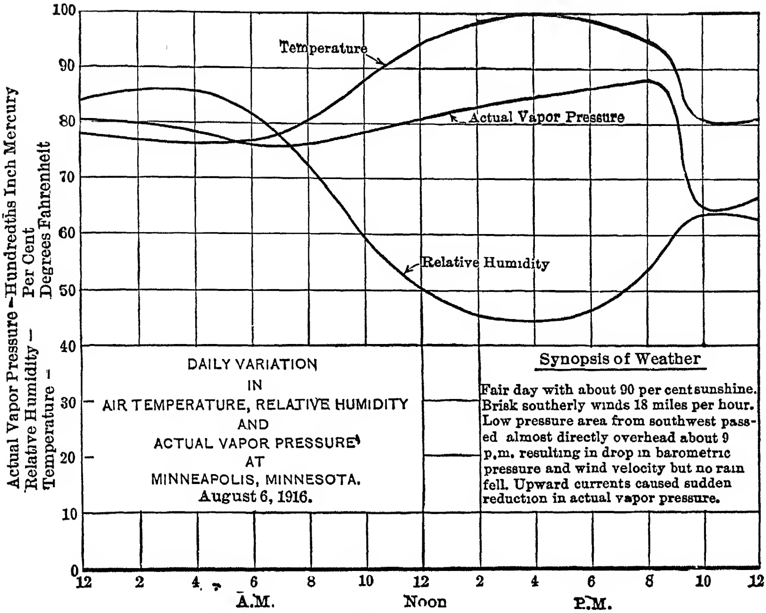


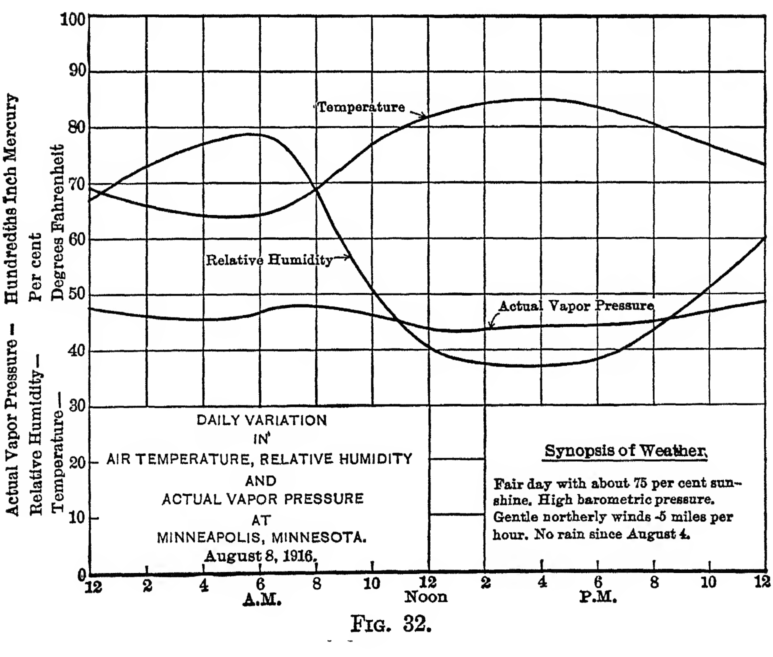
Fig. 30.

Specific Heat of Air. — Whenever a unit volume of dry air is permitted to expand under constant pressure, while being heated, .2375 unit of heat is required to raise its temperature 1° C. A little more than one quarter (.2867) of the heat energy applied is expended in the work of expansion, and the remainder (.7133 or .1694 heat units) goes to heat the air. If the volume of the air is kept constant, only .1694 unit of heat is required to produce the same increase in temperature. The former figure is known as the specific heat of dry air at constant pressure, and the latter, as the specific heat at constant volume.



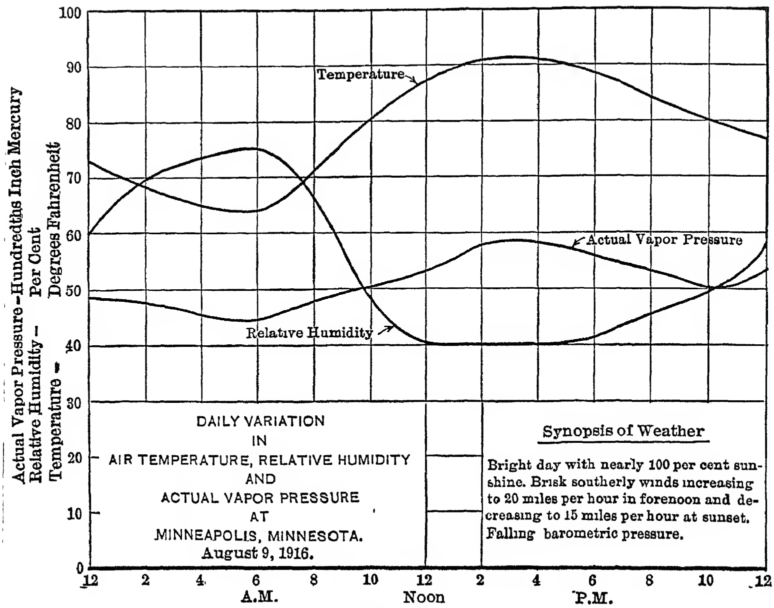
Temperature
Actual Vapor Pressure
Relative Humidity
DAILY VARIATION
IN
AIR TEMPERATURE, RELATIVE HUMIDITY
AND
ACTUAL VAPOR PRESSURE
AT
MINNEAPOLIS, MINNESOTA.
August 6, 1916.
Synopsis of Weather
Fair day with about 90 per cent sunshine. Brisk southerly winds 18 miles per hour. Low pressure area from southwest passed almost directly overhead about 9 p.m. resulting in drop in barometric pressure and wind velocity but no rain fell. Upward currents caused sudden reduction in actual vapor pressure.
Actual Vapor Pressure—Hundredths Inch Mercury
Relative Humidity—Per Cent
Temperature—Degrees Fahrenheit
A.M.
Noon
P.M.

FIG. 31.



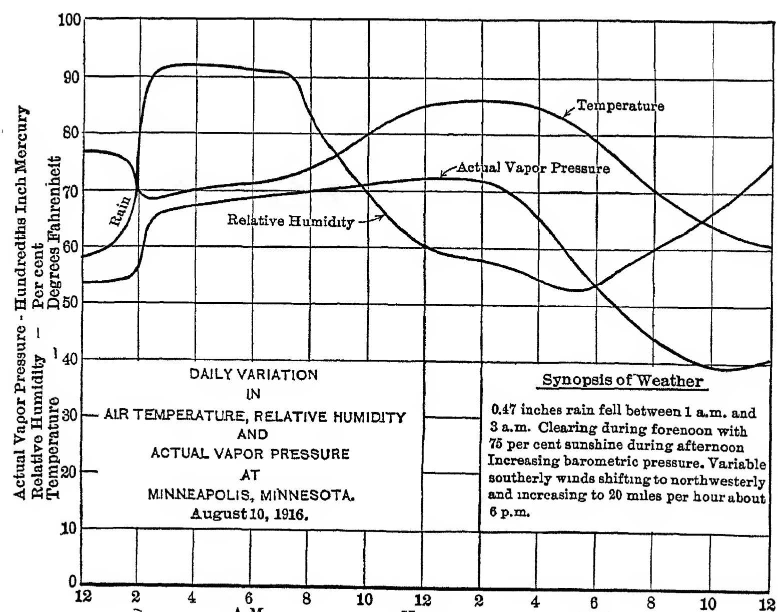
Temperature
Relative Humidity
Actual Vapor Pressure
DAILY VARIATION
IN
AIR TEMPERATURE, RELATIVE HUMIDITY
AND
ACTUAL VAPOR PRESSURE
AT
MINNEAPOLIS, MINNESOTA.
August 8, 1916.
Synopsis of Weather
Fair day with about 75 per cent sunshine. High barometric pressure. Gentle northerly winds 5 miles per hour. No rain since August 4.
Actual Vapor Pressure—Hundredths Inch Mercury
Relative Humidity—Per cent
Temperature—Degrees Fahrenheit
A.M.
Noon
P.M.

FIG. 32.



Actual Vapor Pressure - Hundredths Inch Mercury
Relative Humidity - Per Cent
Temperature - Degrees Fahrenheit
Temperature
Actual Vapor Pressure
Relative Humidity
DAILY VARIATION
IN
AIR TEMPERATURE, RELATIVE HUMIDITY
AND
ACTUAL VAPOR PRESSURE
AT
MINNEAPOLIS, MINNESOTA.
August 9, 1916.
Synopsis of Weather
Bright day with nearly 100 per cent sunshine. Brisk southerly winds increasing to 20 miles per hour in forenoon and decreasing to 15 miles per hour at sunset. Falling barometric pressure.
A.M.
Noon
P.M.

FIG. 33.



Actual Vapor Pressure - Hundredths Inch Mercury
Relative Humidity - Per cent
Temperature - Degrees Fahrenheit
Rain
Temperature
Actual Vapor Pressure
Relative Humidity
DAILY VARIATION
IN
AIR TEMPERATURE, RELATIVE HUMIDITY
AND
ACTUAL VAPOR PRESSURE
AT
MINNEAPOLIS, MINNESOTA.
August 10, 1916.
Synopsis of Weather
0.47 inches rain fell between 1 a.m. and 3 a.m. Clearing during forenoon with 75 per cent sunshine during afternoon Increasing barometric pressure. Variable southerly winds shifting to northwesterly and increasing to 20 miles per hour about 6 p.m.
A.M.
Noon
P.M.

FIG. 34.

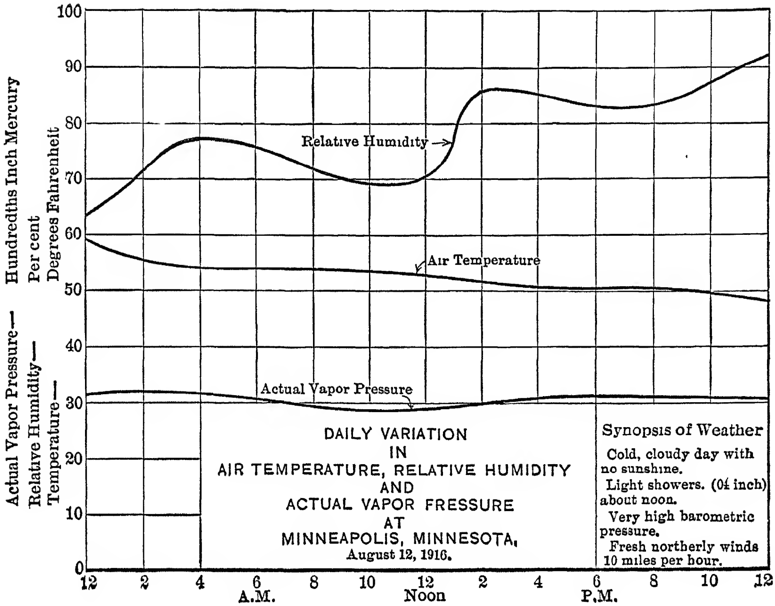

100
90
80
70
60
50
40
30
20
10
0
Actual Vapor Pressure— Hundredths Inch Mercury
Relative Humidity— Per cent
Temperature— Degrees Fahrenheit
Relative Humidity
Air Temperature
Actual Vapor Pressure
DAILY VARIATION
IN
AIR TEMPERATURE, RELATIVE HUMIDITY
AND
ACTUAL VAPOR FRESSURE
AT
MINNEAPOLIS, MINNESOTA,
August 12, 1916.
Synopsis of Weather
Cold, cloudy day with no sunshine.
Light showers. (04 inch) about noon.
Very high barometric pressure.
Fresh northerly winds 10 miles per hour.
12 2 4 6 8 10 12 2 4 6 8 10 12
A.M.
Noon
P.M.

FIG. 35.

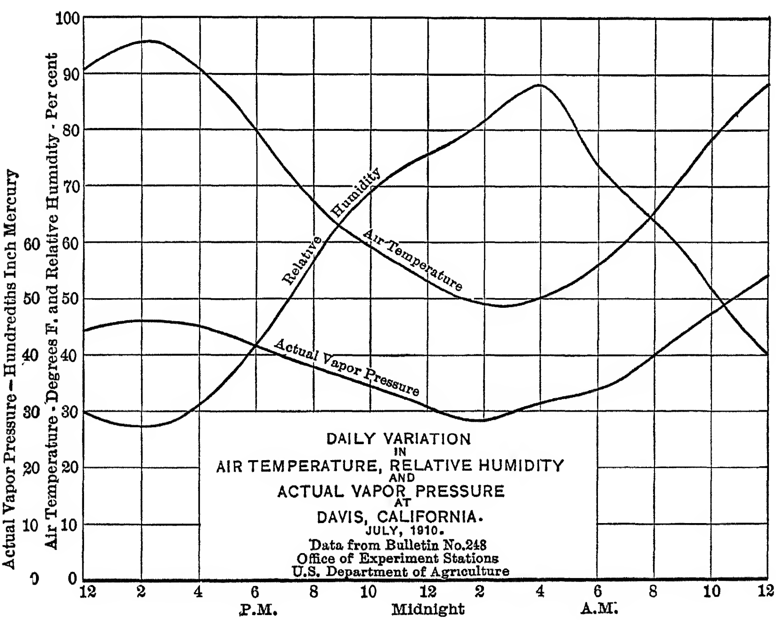

100
90
80
70
60
50
40
30
20
10
0
Actual Vapor Pressure — Hundredths Inch Mercury
Air Temperature - Degrees F. and Relative Humidity - Per cent
Relative Humidity
Air Temperature
Actual Vapor Pressure
DAILY VARIATION
IN
AIR TEMPERATURE, RELATIVE HUMIDITY
AND
ACTUAL VAPOR PRESSURE
AT
DAVIS, CALIFORNIA.
JULY, 1910.
Data from Bulletin No.248
Office of Experiment Stations
U.S. Department of Agriculture
12 2 4 6 8 10 12 2 4 6 8 10 12
P.M.
Midnight
A.M.

FIG. 36.

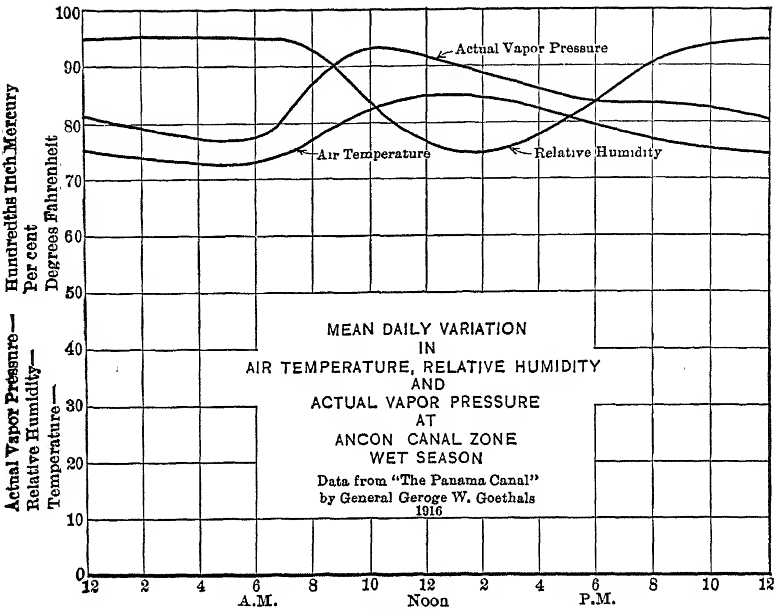

Actual Vapor Pressure—Hundredths Inch Mercury
Relative Humidity—Per cent
Temperature—Degrees Fahrenheit
100
90
80
70
60
50
40
30
20
10
0
Actual Vapor Pressure
Air Temperature
Relative Humidity
MEAN DAILY VARIATION
IN
AIR TEMPERATURE, RELATIVE HUMIDITY
AND
ACTUAL VAPOR PRESSURE
AT
ANCON CANAL ZONE
WET SEASON
Data from "The Panama Canal"
by General Geroge W. Goethals
1916
12 2 4 6 8 10 12 2 4 6 8 10 12
A.M.
Noon
P.M.

FIG. 37.

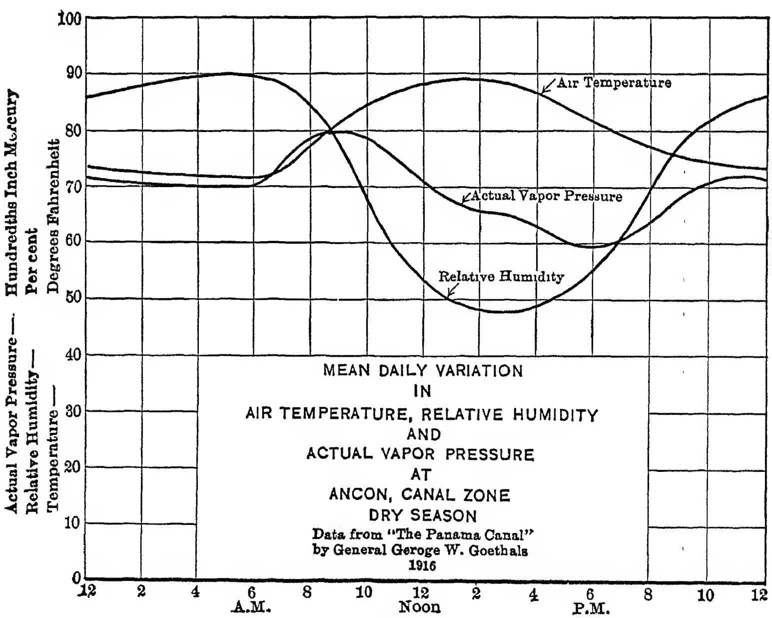

Actual Vapor Pressure—Hundredths Inch Mercury
Relative Humidity—Per cent
Temperature—Degrees Fahrenheit
100
90
80
70
60
50
40
30
20
10
0
Air Temperature
Actual Vapor Pressure
Relative Humidity
MEAN DAILY VARIATION
IN
AIR TEMPERATURE, RELATIVE HUMIDITY
AND
ACTUAL VAPOR PRESSURE
AT
ANCON, CANAL ZONE
DRY SEASON
Data from "The Panama Canal"
by General Geroge W. Goethals
1916
12 2 4 6 8 10 12 2 4 6 8 10 12
A.M.
Noon
P.M.

FIG. 38.

Dynamic Cooling. — If, now, no heat is communicated to the air, and the pressure is reduced $\frac{1}{273}$ part, the air will expand $\frac{1}{273}$ part of its volume, and the heat used in the work of expansion will be drawn from the air itself, resulting in a cooling of .2867 degree. To cool dry air 1° C. it must be permitted to expand $\frac{1}{78.27}$ part of its volume. In a homogeneous atmosphere of uniform, sea level density, a volume of air raised 100 meters would encounter a reduction of $\frac{1}{78.27}$ in pressure, resulting in a cooling of 1° C. Similarly a volume of air raised 185 feet would expand and cool 1° F. This assumes that the given volume of air would be raised so rapidly as not to receive heat from the surrounding air.

The expansion of rising air containing unsaturated water vapor, by giving a larger space to the same number of molecules of vapor, results in a reduction in vapor pressure proportional to the reduction in barometric pressure. On the other hand, the cooling of the air with its vapor content, through the work of expansion, decreases its capacity for vapor to a greater extent, hence, condensation will ultimately occur. The distance in feet, which unsaturated water vapor must rise above the earth's surface to effect condensation of the vapor through the cooling resulting from expansion is approximately equal to 225 times the difference, in degrees Fahrenheit, between the ordinary air temperature and its dew-point temperature.

Ascending air containing saturated water vapor cools much more slowly than dry air because the reduction in temperature results in a condensation of some of the vapor, and the heat so liberated supplies some of the heat required in the work of expansion, thus preventing the air from cooling as rapidly as it otherwise would. The higher the temperature of the air the more water vapor it would contain at saturation, consequently, the slower it would cool upon rising. At sea-level, for example, saturated vapor at a temperature of 32° F. would cool 1° F. in rising 285 feet. If the temperature of the vapor is 68° F. it would cool 1 degree in rising 425 feet. At an elevation of about

$2\frac{1}{2}$ to 3 miles, where the maximum storm development occurs, vapor at a temperature of 50° F. would cool about 1 degree in rising 425 feet, because the same amount of heat liberated in condensation of vapor has a greater effect in preventing the cooling of the less dense air.

Stable and Unstable Air. — Inasmuch as air containing saturated vapor, upon rising, cools 1 degree for about every 425 feet of ascent, and as the reduction in temperature of the undisturbed surrounding air averages 1 degree for every increase of about 300 feet in altitude, it must be apparent that rising saturated air is continually warmer than the surrounding unsaturated air, and therefore has an increasing tendency to rise, with the resulting precipitation of its vapor content, *i.e.*, such air is in unstable equilibrium.

Air containing unsaturated water vapor, however, upon being given an impulse upward, cools 1 degree for the first 185 feet of ascent above the earth's surface; hence it quickly becomes cooler and consequently heavier than the surrounding undisturbed atmosphere and tends to fall back to its original position, *i.e.*, such air is in stable equilibrium.

Effect of Vapor on Weight of Air. — Since the specific gravity of water vapor is only a little more than six tenths of the specific gravity of dry air at the same temperature and pressure, it follows that the pressure of water vapor at a given temperature is greater than the pressure of an equal amount of dry air at the same temperature. At a temperature of 80° F., for example, the maximum elastic pressure of water vapor is equal to about 1 inch of mercury. A cubic foot of dry air at 80° F. and 30 inches barometric pressure weighs .0735 lb. If part of the air is replaced by water vapor under the same pressure until the space is saturated with vapor, about one thirtieth of the volume of air will be displaced. The elastic pressure will remain the same but the weight of the cubic foot of air and vapor will be reduced to .0726 lb.

The weights of dry air and of air containing saturated water

vapor at the given temperature, *i.e.*, air at 100 per cent relative humidity, and under 30 inches barometric pressure, are graphically shown in Fig. 39.

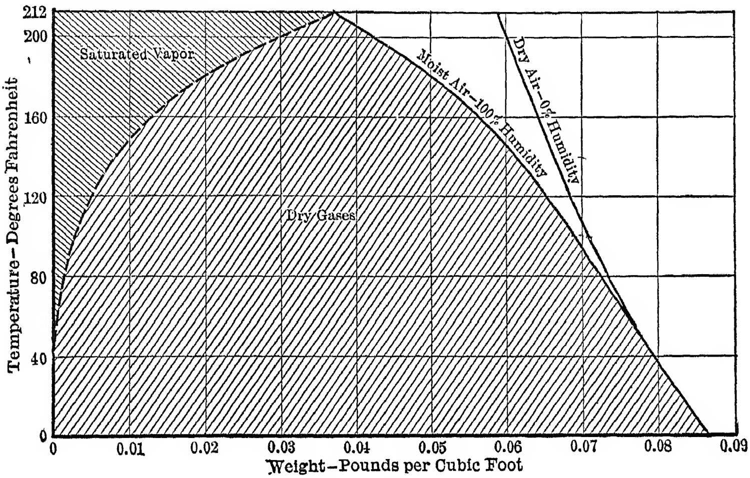


FIG. 39. — Effect of Temperature on Weight of Dry and Moist Air under Pressure of 30 Inches Mercury.

CHAPTER IV

PRECIPITATION: ITS OCCURRENCE AND DISTRIBUTION

Dew and Frost. — Whenever the water vapor in the air is cooled down below the temperature corresponding to the pressure of saturated vapor, condensation occurs on dust particles, globules of water, grass, or other foreign objects.

During summer nights grass and other forms of vegetation, being good radiators of heat, soon cool down the surrounding air to a point where some of the moisture is precipitated out in the form of dew. If the dew-point temperature is below 32° F. and the night cool, moisture may be condensed out in the form of hoar frost.

In arid regions dew is often an appreciable source of water supply for the scant vegetation found in such regions, as it forms mainly on the plants and not on the barren soil.

Rain, Snow, etc. —Condensation of moisture out of the atmosphere above the immediate surface of the earth occurs on dust particles or suspended globules of water and takes the form of fog, cloud, rain, snow or hail. The condensation which results in the precipitation of moisture from clouds is caused by what is known as "dynamic cooling," *i.e.*, the cooling resulting from the consumption of heat in the work of expansion of the rising vapor, as previously explained.

It is a common misconception that almost all of the rain which falls on the land comes from moisture evaporated from the ocean. As a matter of fact, the greater portion of the rain which falls in the United States is water re-precipitated after having fallen as rain and having evaporated from the land area. Only that portion of the rainfall which runs off

through the streams back into the ocean represents water which was evaporated from the ocean. The remainder represents rain which fell on the land, was evaporated from the land, condensed from the atmosphere over the land, and re-precipitated as rainfall. The portion of the rainfall which is derived from the moisture evaporated over the ocean varies in different parts of the country. In those regions where the prevailing winds are off the ocean, the greater portion of the rainfall naturally represents moisture evaporated from the ocean. Among such regions are the Pacific slope and the region bordering the Gulf of Mexico. The Upper Mississippi and Missouri valleys and the eastern slope of the Rocky Mountains are typical of the areas which derive most of their rainfall from moisture evaporated from the land.

Convective Precipitation. — In the equatorial regions the principal air movement is vertical. The result of these vertical or convection currents is that the air in moving upward expands and cools, causing precipitation. The heating of the lower strata of air during the forenoon accentuates the upward movement, causing daily rains during the afternoon. The radiation of heat during the early evening usually arrests the convection currents, and results in a cessation of rainfall.

Orographic Precipitation. — In the mountainous regions, such as on our Pacific Coast, the air is forced upward when it reaches the mountain ranges, expands, cools and precipitates its moisture. Fig. 40, from the June, 1914, Monthly Weather Review illustrates the formation of clouds and the precipitation of moisture in this manner.

On the leeward side of the mountains, the air descends, absorbs moisture, and gives rise to arid regions.

Cyclonic Precipitation. — As stated, briefly, on page 29, the unequal heating of the earth's land and water masses results in more or less permanent regions of high and low barometric pressure. This fact is shown in Figs. 41 and 42,* which give

* Courtesy Ginn and Company.

the mean sea level isobars, or lines of equal barometric pressure, for the world, during January and July. A mean difference equal to about half an inch of mercury will be noted between the pressure over the oceans and over the land. This difference is sufficient to set the air masses in motion.

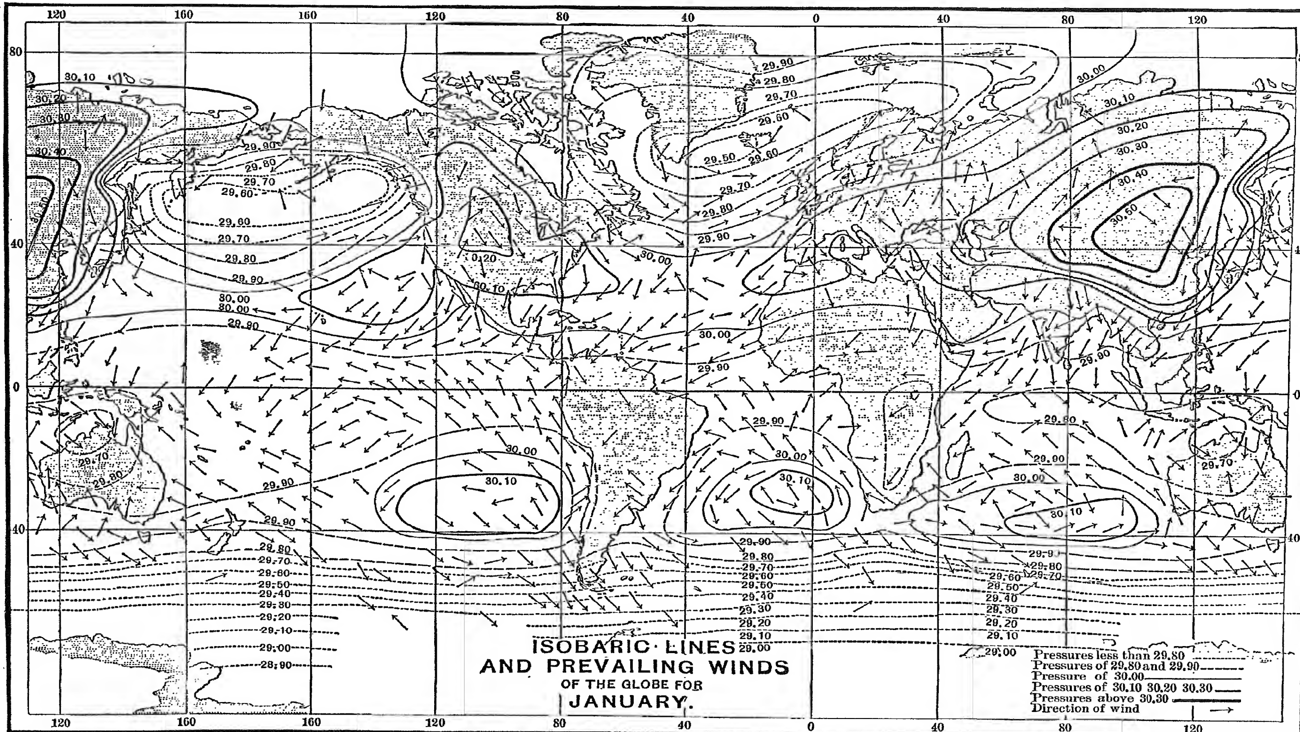
The maximum development of storms is limited to an average elevation of about three miles.

FIG. 40. — Mount Lowe, Cal., during the Rain of February 20, 1914.

Fig. 43 shows in a general way the mean tracks of the high- and low-pressure areas across the United States. Individual storms, of course, usually depart considerably from the mean tracks. This is well illustrated in Fig. 44 taken from "Weather Forecasting in the United States," U. S. Weather Bureau, 1916.

The rate of translation of these storm centers depends upon the pressure gradient between them. The following table gives the wind velocity resulting from given differences in pressure between two localities 500 miles apart.

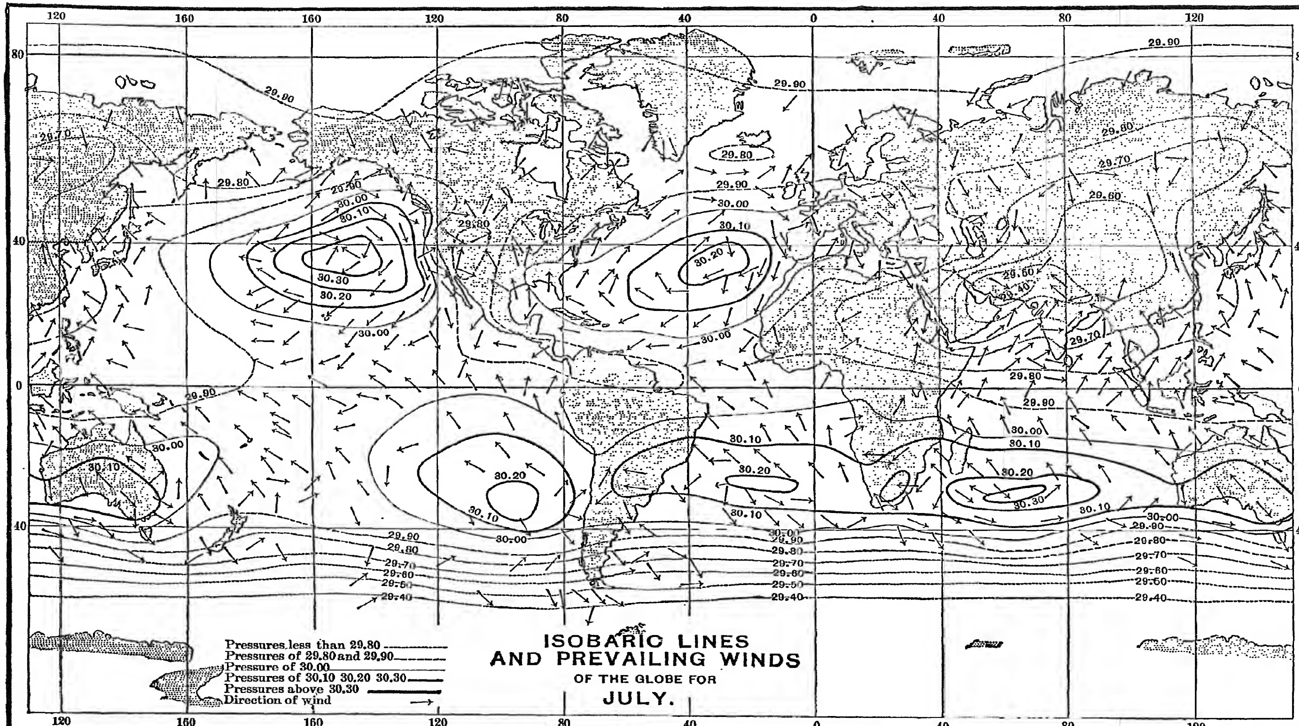
Pressure gradient, inches mercury in 500 miles	Wind velocity, miles per hour
0.43	10
0.48	15
0.52	22
0.62	30
0.76	35



From Buchan's "Challenger" Report.

Bradley & Poates Engrs, N.Y.

Fig. 41.



From Buchan's "Challenger" Report.

Bradley & Poates Engrs, N.Y.

FIG. 42.

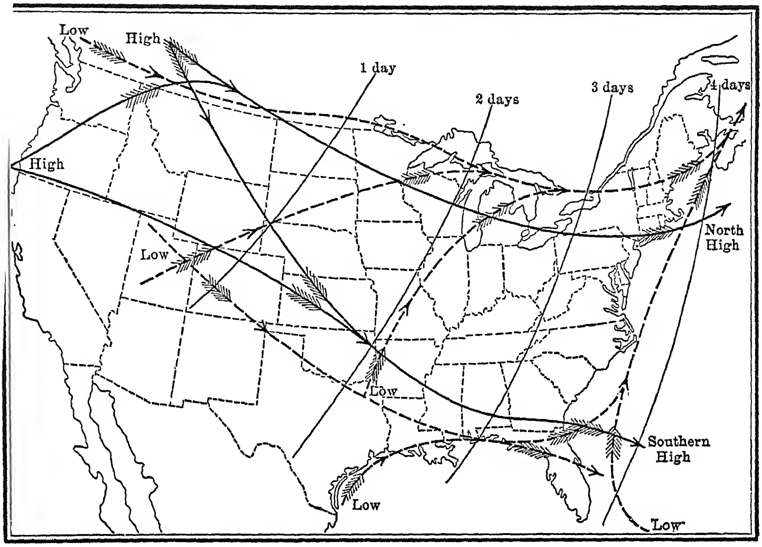


FIG. 43. — Mean Tracks and Average Daily Movement of Storms in the United States.

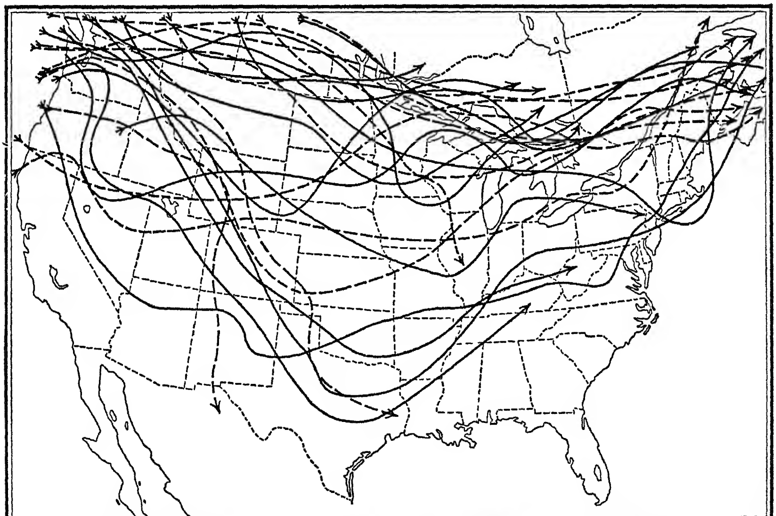


FIG. 44. — Paths of North Pacific Lows, January, 1900–1909.

The monthly mean velocity of cyclones and anticyclones passing over the United States between 1878 and 1904 is shown in the following table:

AVERAGE VELOCITY OF STORMS IN UNITED STATES

U. S. Weather Bureau, 1878–1904

(Velocity in miles per hour)

	Jan.	Feb	Mch.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Cyclones (3276).....	34 8	34 8	31 6	26 9	24 3	24 0	24 4	24.6	24.8	27.4	30.7	34.9	28.6
Anticyclones (1587)...	29 5	28 2	26.7	25 2	25 4	23 7	22.2	22 1	24.7	24.7	27.1	27.4	25.6

"Lows." — An area over which low barometric pressure prevails is spoken of as a "low" or "cyclonic" area, and one over which high barometric pressure prevails as a "high" or "anticyclonic" area. Cyclonic weather is characterized by increasing surface temperature, easterly winds increasing in intensity, decreasing barometric pressure, increasing cloudiness, and precipitation. The air over a low-pressure area moves inward and upward, and, in the northern hemisphere, in more or less regular, counter-clockwise, rotary paths. The low-pressure areas are roughly circular and vary from about 500 to 1500 miles in diameter.

"Highs." — After the low area has passed the barometric pressure increases, the clouds break, the winds shift to the west, and anticyclonic weather sets in. Its characteristics are high barometric pressure, low temperature, clear skies, increasing westerly winds moving downward and outward from the center of the high-pressure area in approximately clockwise, rotary parts.

As previously stated, temperature and pressure gradients between land and water masses and between poles and equator, together with the rotation of the earth, give rise to the general circulation of the atmosphere. Cyclones and anticyclones appear to be whirls of dynamic origin, in the larger air movements,

and not the result of local convection currents. Cyclonic activity is limited to the lower layer of air about five miles in thickness, above which the temperature changes are slight. In the upper levels of the fleecy, cirrus clouds there is the permanent eastward drift of air at velocities of about 90 miles per hour.*

Thunderstorms. — During warm weather cyclonic areas are usually accompanied by thunderstorms. Fig. 45 taken from the Monthly Weather Review of June, 1914, is a typical diagrammatic representation of a thunderstorm, and Fig. 46 shows the changes in meteorological elements during such a storm. The upward rush of moist air in a cyclone results in the formation of the cumulus clouds typical of thunderstorms.

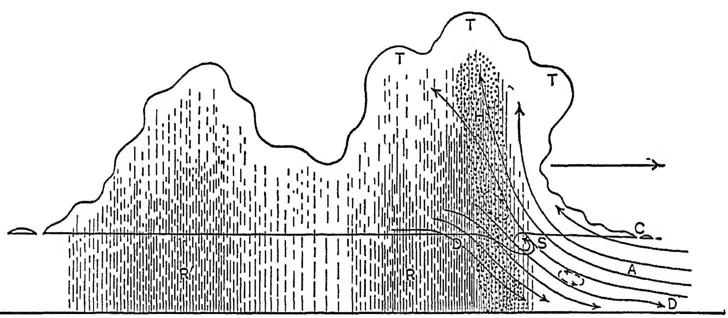


FIG. 45. — Diagrammatic Representation of a Thunderstorm. *A*, ascending air; *D*, descending air; *C*, storm collar (Sturmkragen); *S*, roll scud; *D*, wind gust; *H*, hail; *T*, thunderheads; *R*, primary rain; *R'*, secondary rain.

A thunderstorm, as the name implies, is a storm accompanied by lightning and thunder and, usually, precipitation. According to Simpson† the electricity whose discharge constitutes the lightning of the thunderstorm is generated by the breaking up of falling rain drops encountering strong upward currents. The resulting spray is carried upward and the small drops,

* For a fuller discussion of this phase of the subject see Professor Bigelow's report, "The International Cloud Observations," Annual Report, Chief of Weather Bureau, 1898–1899, and Monthly Weather Review, November, 1914, and April, 1916.

† Simpson, Dr. G. C., in Memoirs, Indian Meteorological Department.

through coalescence, soon grow so large as to fall again. Coalescence and disruption proceed rapidly and the electrical charge within the cloud grows. The positive charge in the cloud draws an excess of negative electricity to the ground underneath or to a nearby cloud until a current of electricity, visible as

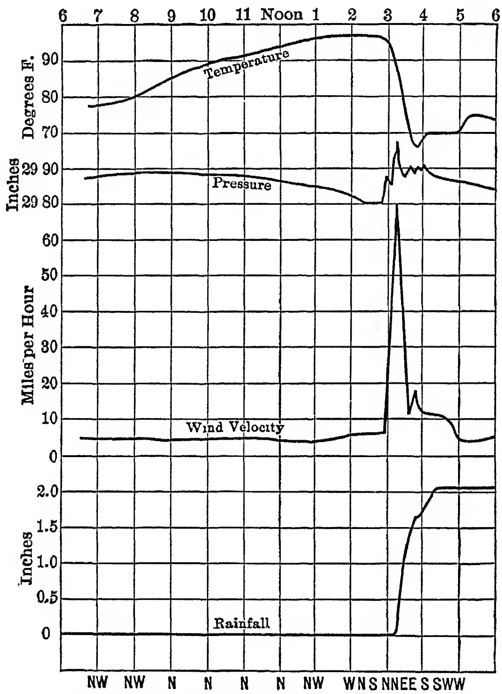


FIG. 46. — Course of Meteorological Elements during a Thunderstorm at Washington, D. C. (July 30, 1913).

lightning, flows through the intermediate air, heating it in its passage and setting up the familiar, violent sound wave through the sudden expansion of the heated air along the path of discharge. During thunderstorms, ozone, nitrous oxide and ammonia are produced and carried to earth by rain, adding in small though appreciable measure to the fertility of the soil.

Thunderstorms occur with varying frequency both as to time and locality. South of latitude 40 degrees, excepting both

Atlantic and Pacific coasts where they occur less frequently, the average occurrence of thunderstorms is from 50 to 75 a year. By far the greater number occur between the months of April and September. In general the frequency varies from about 75 a year in the Gulf region and in New Mexico to 20 a year along the northern border of the United States with less than 10 a year, on an average, in the Pacific Coast states.

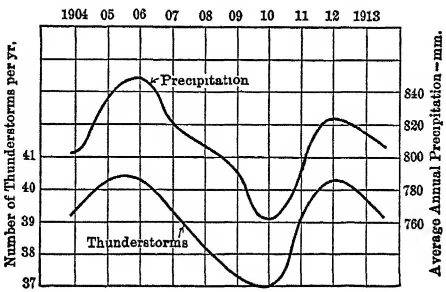


FIG. 47. — Relation between Precipitation and Thunderstorms in the United States.

Thunderstorms appear to be most frequent in years of high rainfall which, considering the world as a whole, are also warm years. Fig. 47 taken from the June, 1914, Monthly Weather Review shows the relation between the annual number of thunderstorms and average annual precipitation at 127 stations in the United States.

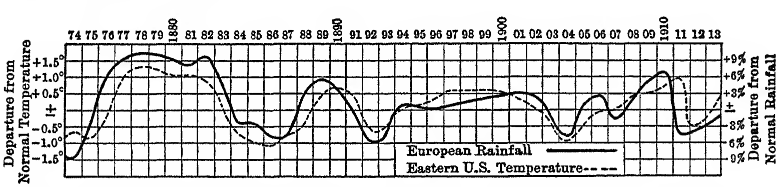


FIG. 48. — Relation of Temperature in Eastern United States to Rainfall in Europe.

Fig. 48 taken from the same source shows the relation between the temperature in the Eastern United States and the rainfall in Europe. Both sets of curves are smoothed to eliminate minor irregularities.

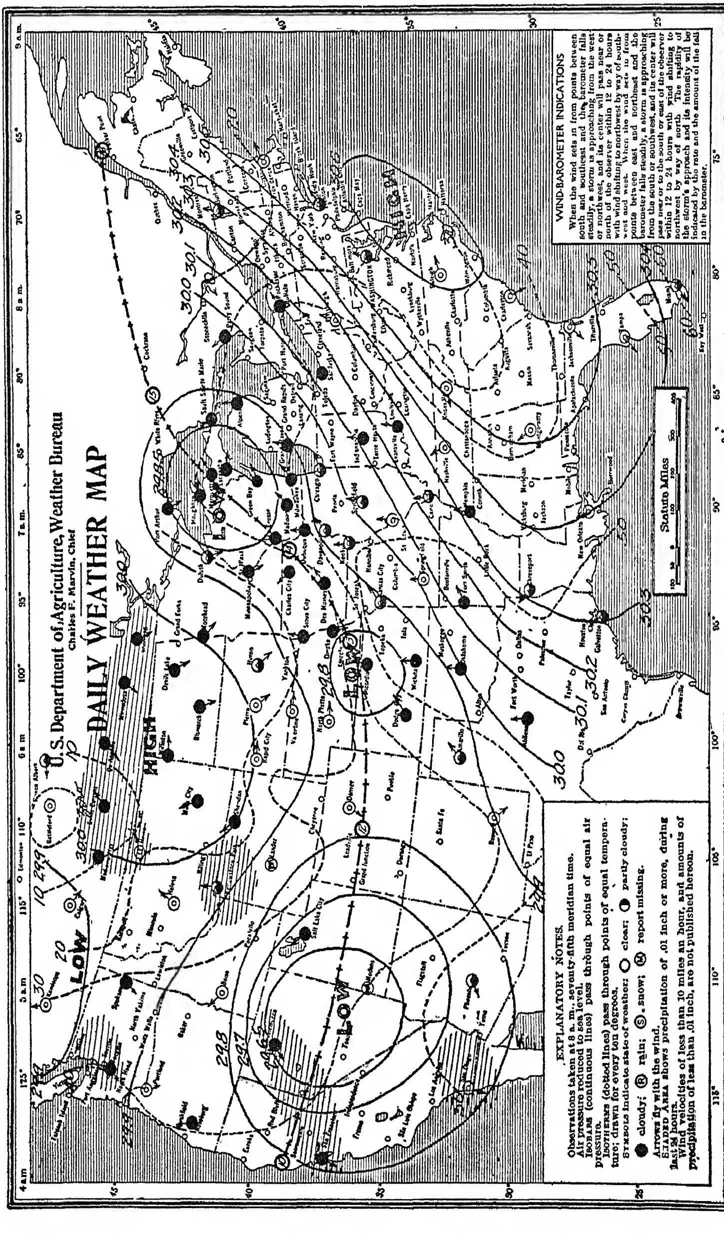


FIG. 49. — Daily Weather Map for Feb. 11, 1915.

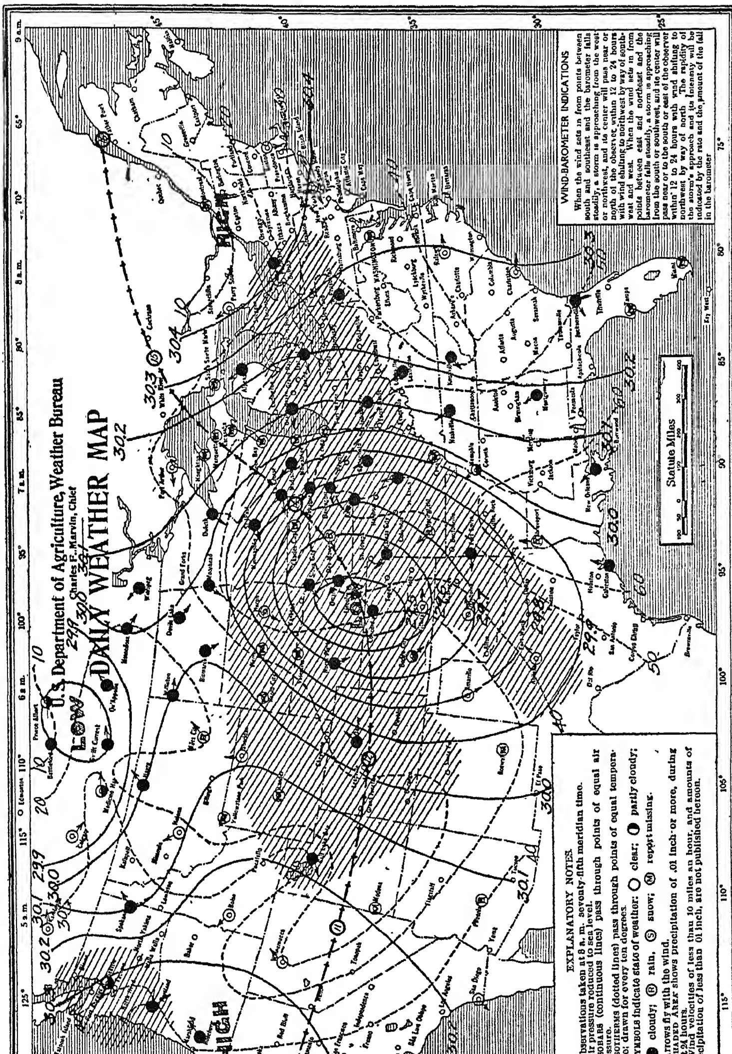


FIG. 50. — Daily Weather Map for Feb. 13, 1915.

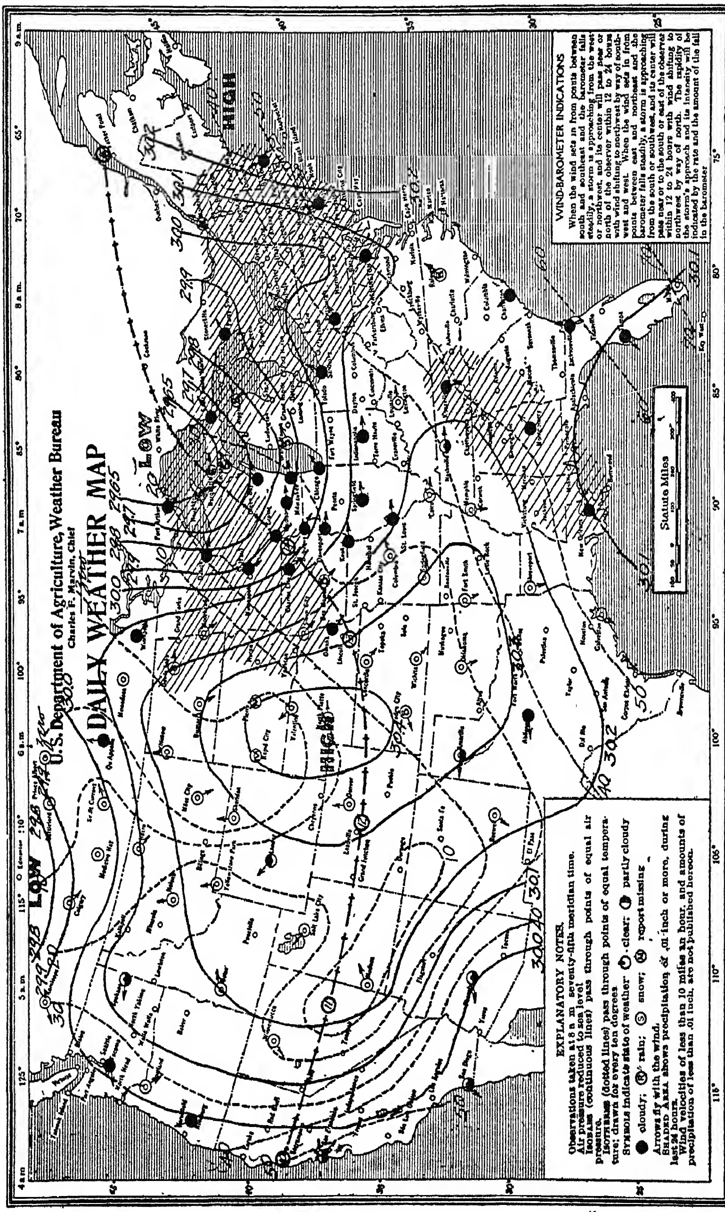


FIG. 51. — Daily Weather Map for Feb. 15, 1915.

Weather Forecasts. — Daily weather forecasts are made by the United States Weather Bureau on the basis of the preceding twenty-four hours' observations at about 200 telegraphic reporting stations. These forecasts take the form of official statements of weather probabilities, weather maps, special warnings to lake and coasting vessels, flood warnings, instructions to shippers, and the display of weather flags. All observations used in forecasting the weather, such as observations of barometric pressure, temperature, direction and velocity of wind, relative humidity, precipitation and sunshine, are made at 8 A.M. and 8 P.M. 75 Meridian time, and the data are immediately telegraphed in cipher to the main office at Washington and also to a number of large cities where forecasters are stationed. Here the data are quickly transferred to a base map, the forecasts made, and the "Daily Weather Map" immediately printed and placed in the mails so as to be available for use by the general public as promptly as transportation facilities permit.

Figs. 49 to 51 show typical "Daily Weather Maps" for February 11, 13 and 15, 1915, with the exception of the Minneapolis local forecast and the record of observations at the principal telegraphic reporting stations. Except for the reduction in scale and difference in drafting, these figures are exact copies of the actual daily weather maps issued by the local office on the given dates. The path of the dominating low-pressure area has been added to the maps to facilitate their study and interpretation.

Any person thoroughly familiar with the phenomena and the principles that underlie our weather conditions can do considerable "forecasting," even without the aid of any instruments, by merely observing the outstanding weather characteristics in his locality. The wind is perhaps the best weather indicator. Its significance is succinctly stated on the "Daily Weather Map" in the following language:

Wind-Barometer Indications

"When the wind sets in from points between south and southeast and the barometer falls steadily a storm is approaching from the west or northwest, and its center will pass near or north of the observer within 12 to 24 hours with wind shifting to northwest by way of southwest and west. When the wind sets in from points between east and northeast and the barometer falls steadily a storm is approaching from the south or southwest, and its center will pass near or to the south or east of the observer within 12 to 24 hours with wind shifting to northwest by way of north. The rapidity of the storm's approach and its intensity will be indicated by the rate and the amount of the fall in the barometer."

Measurement of Precipitation. — Precipitation is regularly recorded in the United States at nearly 6000 stations. Of these about 200 constitute the "regular" or "telegraphic-reporting" stations, at which a full record is kept of such meteorological phenomena as amount and rate of precipitation, temperature, relative humidity, direction and velocity of wind, sunshine, the occurrence of frosts, aurora, thunderstorms and the like. At most of the remaining stations, known as "coöperative observer" stations, record is kept only of rainfall and snowfall, maximum and minimum temperature, and general information regarding such phenomena as frost, sunshine, auroras, and the like.

Standard Rain Gage. — Coöperative observers are furnished with a standard rain gage, Fig. 52, and maximum and minimum thermometers. A typical coöperative observer station is shown in Fig. 6, page 20.

The standard rain gage consists of a funnel-shaped collector *A* eight inches in diameter at the top, a measuring tube *C*, 20 inches high and 2.53 inches in diameter, *i.e.*, one tenth

the area of cross section of the receiver, an overflow attachment B and a measuring stick graduated to read directly to inches depth of precipitation.

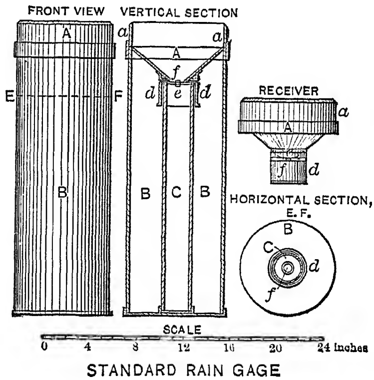


FIG. 52.

Rain falling into the receiver A runs down through the small opening e into the measuring tube C where the depth can be measured with the graduated stick. If the rainfall exceeds 2 inches, the measuring tube C overflows into B, from which the observer later refills the tube C for measurement.

When used as a snow gage the funnel A and the measuring tube C are removed and the overflow cylinder B is used to catch the precipitation directly.

Tipping-bucket Gage. — At the regular Weather Bureau stations, where a continuous record of rainfall is obtained, a recording gage known as the "tipping-bucket" gage illustrated in Fig. 53 is employed. Rain falling into the collector, which is 12 inches in diameter, runs into the bucket through a funnel attached to the bottom of the collector. The bucket is divided into two parts, and is mounted on trunnions so placed that when one part of the bucket is filled, it tips over and empties its contents into the reservoir below. The bucket is usually adjusted so that it tips for each one-hundredth inch rainfall. At high rates of rainfall, amounting to a bucketful every few seconds, a correction must

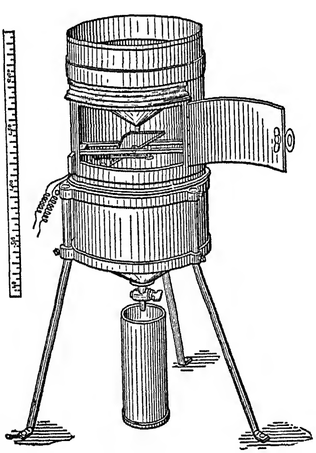


FIG. 53. — Tipping-bucket Rain Gage

be made to the record because each bucket, during the tipping motion, becomes overfilled. By means of an electrical circuit which is closed and opened at each tip of the bucket, each one-hundredth inch of rain is recorded by a pen on a clock-operated record sheet. Check readings of the total amount of precipitation are made by measuring the water in the reservoir.

Marvin Float Gage. — Another type of recording rain gage which has wide application is the Marvin float gage, illustrated in Fig. 54. An 8-inch collector protected by a 21-inch windshield gathers the rainfall into a reservoir. A record of the precipitation is secured by means of a float on the surface of the water in the reservoir actuating a pen which traces the record on a clock-operated record sheet. The recording apparatus is contained in the square portion of the apparatus. An eight-day record is secured without attention and the precipitation can be estimated from the record sheet to hundredths of an inch. About one fourth inch of kerosene is kept on the water in the receiver to prevent evaporation. The gage has a total capacity of 10 inches rainfall and may be conveniently emptied through the spigot provided, which permits draining the receiver only to the point where the float has returned to the zero mark.

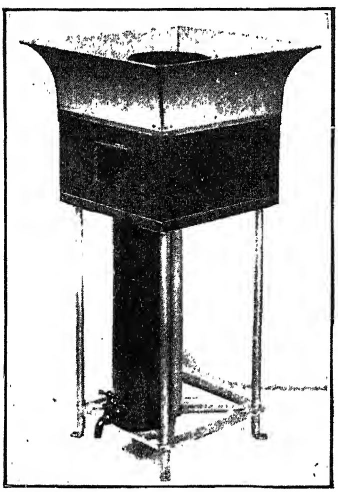


FIG. 54. — Marvin Float Gage with Wind Shield.

A number of other automatic rain gages, used outside of the U. S. Weather Bureau, are on the market.

Exposure of Rain Gage. — Rather more important than the selection of the rain gage, however, is the placing of it. The primary disturbing influence is the wind. The following table gives some observations of the decrease in the catch

of the rain gage with increase in elevation of the gage above the surface of the ground, primarily, because of the effect of the wind at the higher levels.

Elevation of rain gage	Relative catch of rain gage
Feet	
0	1.00
43	0 75
85	0 64
194	0 58

In small towns the rain gage can usually be placed on the ground in an open lot surrounded by a fence or low bushes. No object near the gage should be within a distance equal to its height. The gage should, of course, be free from molestation. In the larger cities the rain gage is usually placed near the center of a large flat roof. The use of wind shields, such as that illustrated in Fig. 54, page 80, has been found to overcome most of the ill effects of the wind. This was forcibly presented, first, by Nipher in St. Louis, in 1878, when he demonstrated that a gage, equipped with his shield, placed on an 18-foot pole above the tower of the university, 118 feet above ground, collected the same amount of rainfall as a shielded gage placed on the ground.

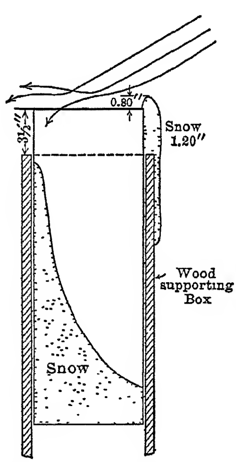


FIG. 55.—Action of Ordinary Snow Gage during Snowstorm (after Horton).

Measuring Snowfall.—The difficulties encountered in measuring rainfall are accentuated in measuring sleet and snowfall. Light snow is often blown out of the gage again by high winds even after having once lodged in the gage. The action of the ordinary snow gage during a snowstorm is well illustrated by Fig. 55 from an article by Horton.*

* Horton, R. E., Monthly Weather Review, February, 1914, p. 99. See also "The Measurement of Rainfall and Snow" by Robert E. Horton in Journal of the New England Water Works Assoc., 1919.

The catch of the gage in this case was only .43 inch although the total snowfall was 1.41 inches.

The Weather Bureau has long required its observers to measure the snow upon the ground in one or more selected spots where experienced judgment indicates that a normal and representative depth of snowfall is to be found. Satisfactory locations are usually afforded by small open places in wooded parks, small clearings in deep woods with some underbrush or among rather open second growth. By using the gage as a "cookie cutter" a cylinder of new snow can be secured which can be melted by the addition of a known quantity of hot water and the equivalent rainfall determined. Whenever the snow is not melted or weighed its water equivalent is determined by the conventional ratio of ten volumes of snow to one volume of water. Although this constitutes a satisfactory *average* ratio, it deviates widely from the truth at times. In southern latitudes the snow is moist and a higher ratio usually applies. In the latitude of northern Minnesota the snowfall is usually lighter, and 11 to 12 inches and occasionally as high as 30 inches of new snow are required for one inch of water. As the percentage of precipitation which occurs as snow is usually quite small, however, the resulting error in *annual* precipitation is much less than the probable error in the ratio might indicate.

A map of the mean annual snowfall in the United States is given in Fig. 56.

The great depth to which snow falls in places in the West is well illustrated in Fig. 57 taken from the May, 1915, Monthly Weather Review.

When rain, sleet and snow occur together, or when the snow melts as it falls, ground measurements are obviously inapplicable, and a shielded snow gage of the type illustrated in Fig. 58 must be resorted to.

The best method of determining the water content of the total layer of snow on the ground at any time during the

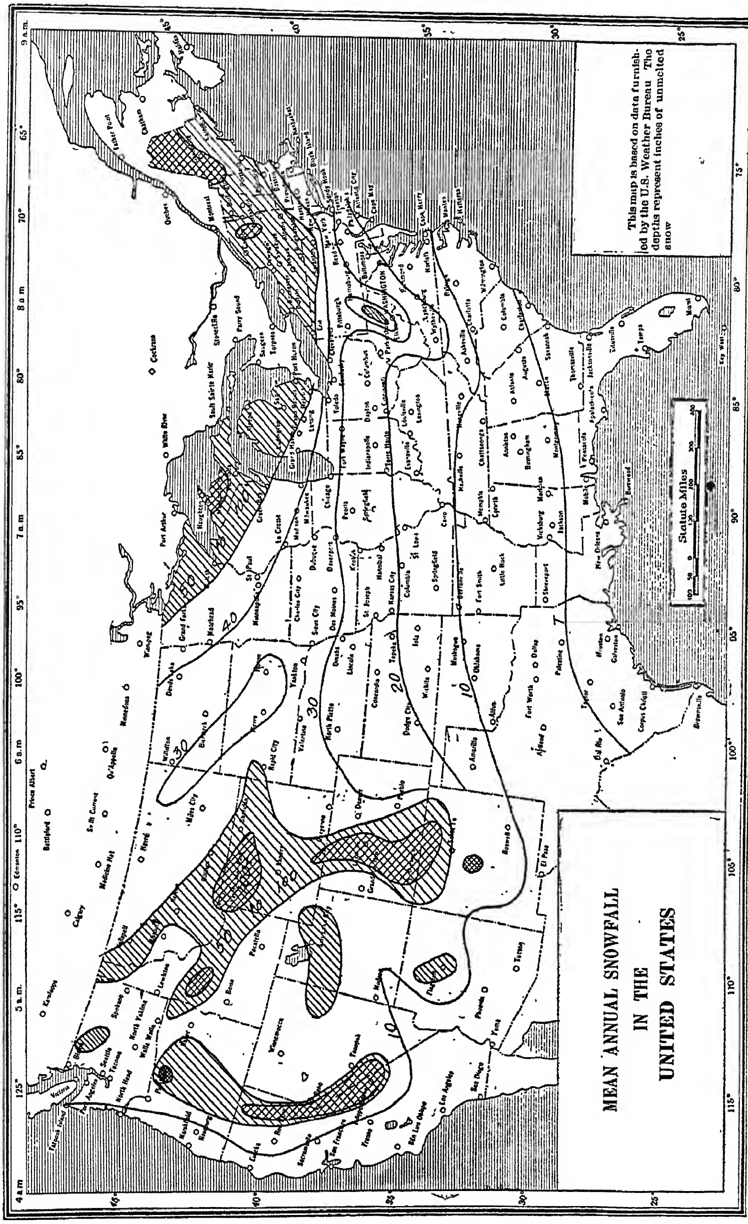

MEAN ANNUAL SNOWFALL IN THE UNITED STATES
This map is based on data furnished by the U.S. Weather Bureau The depths represent inches of unmelted snow
Statute Miles

FIG. 56.

season is by means of weighing a cylinder of snow cut from the snow layer by means of tubes. One type of tube in use by

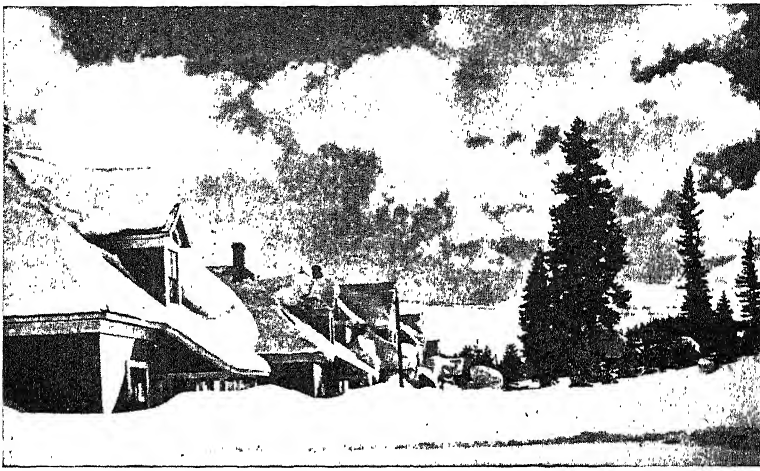


FIG. 57. — Snowfall at Hobart Mill, Cal.

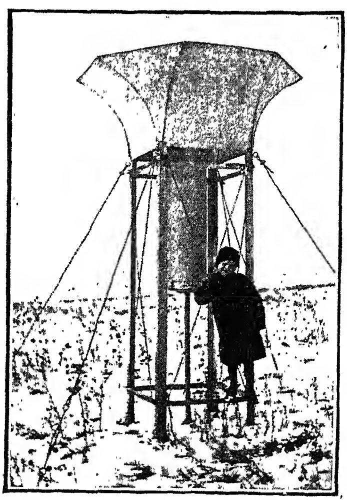


FIG. 58. — Marvin Shielded Snow Gage.

the Weather Bureau is $2\frac{3}{4}$ inches in diameter and of varying length. One end of the tube is fitted with a toothed steel cutting edge. The outside is provided with a scale of inches.

Snow Surveys. — Snow surveys, made shortly before the spring break-up, are often of considerable service in the mountainous regions of the West in predicting the probable supply of water which will be available during the succeeding irriga-

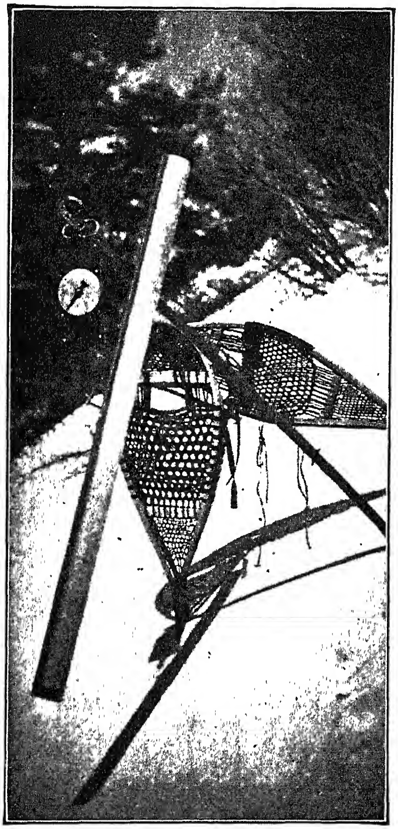


FIG. 59. — Apparatus used in Snow Surveys.

tion season. The apparatus essential for such work is shown in Fig. 59 and the character of the country in which such surveys have been made, is shown in Fig. 60. The depth of snow, especially in rough country, is determined much more frequently than its density. On a topographic map or sketch of the region, the extent of snow cover is shown, together with the depth and

density of the snow as determined by the survey. From these data the equivalent depth of rainfall over the entire area, and hence the approximate available water supply, is determined.*

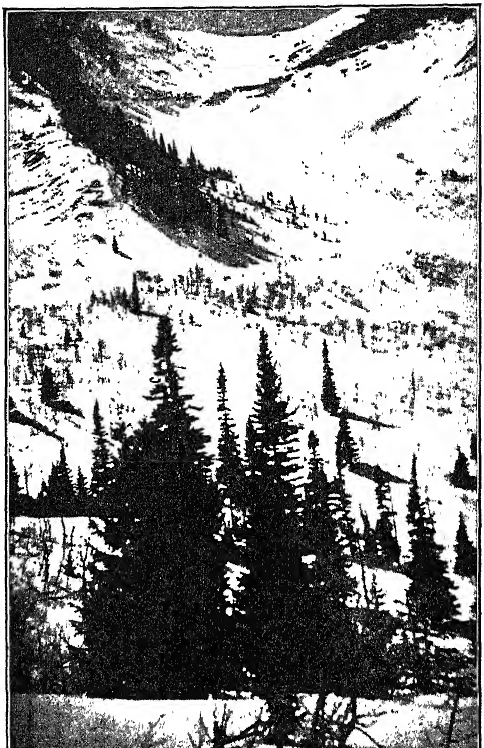


FIG. 60. — Typical Country in which Snow Surveys were made.

Variation of Character of Precipitation with Temperature. — Although the surface air temperature is not an unfailing indication of the character of precipitation by any means, the Weather Bureau records indicate a reasonably constant relationship from year to year in the Northwest.

Fig. 61 shows the monthly mean, and the mean maximum

* The art of making snow surveys and predicting runoff from the data secured has been very fully developed and extensively utilized for 18 years by Prof. J. E. Church of Reno, Nevada. See Eng. News-Record, Feb., 1921, and Jan., 1925.

and minimum temperatures, and the approximate percentage of total precipitation which falls as snow during the various months of the year, at St. Paul and at Moorhead, Minn. For a monthly mean temperature of 23 degrees, the mean of the maximum daily temperatures is approximately 32 degrees, and for a monthly mean temperature of 41 degrees, the mean of the minimum daily temperatures is approximately 32 degrees.

About 30 per cent of the precipitation occurs as snow when the monthly mean temperature is 40 degrees, and practically all of it occurs as snow when the mean temperature is below 20 degrees.

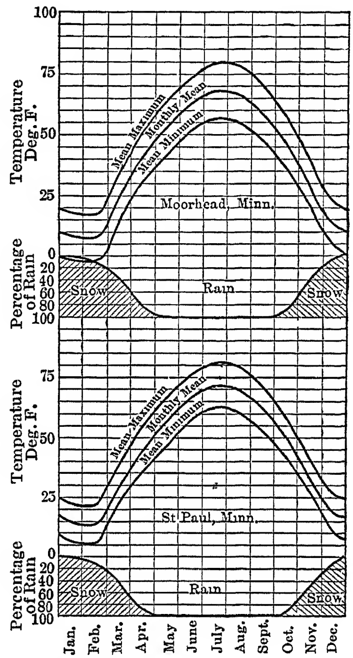


FIG. 61.—Mean Temperatures and Character of Precipitation.

Ice Storms. — The surface air temperature, however, is not always an indication of the character of precipitation. In New England, New York, Pennsylvania, and in the states north of the Ohio River, in particular, rain occasionally falls when the surface air temperature is below freezing. The result is an ice storm. In one New England ice storm, rain fell when the surface air temperature was 23 degrees below freezing.*

While the picture presented by an ice-coated out-of-doors is truly wonderful, the destruction wrought to telegraph, telephone and power-transmission wires and to trees is often severe as is well illustrated in Fig. 62.†

* Ice Storms of New England by Chas. F. Brooks, Cambridge, 1914.

† Variations in Precipitation as Affecting Waterworks Engineering, by Carl P. Birkinbine, Am. W. W. Assoc., Vol. 3, No. 1, March, 1916.

Birkinbine states that of 211 storms, 42.5 per cent showed a sleet thickness of less than one-quarter inch; 29.4 per cent showed a thickness of from one-quarter to one-half inch; 19.9 per cent from one-half to one inch; and 8.1 per cent showed an ice coating of more than one inch.

FIG. 62. — Results of an Ice Storm.

Ice storms are usually very local in character and cannot be predicted with any great certainty. They appear to be most prevalent in the regions of moderate winter temperature and heavy winter precipitation. The essential to the formation of an ice storm is a stratum of air with temperature above freezing overlying a stratum of air near the earth's surface whose temperature is below freezing. Usually the temperature of objects on the earth's surface is also below freezing.

Variation of Precipitation with Latitude, Altitude, etc. — In general, precipitation is greatest at the equator and becomes gradually less towards the poles. In the regions of the tropics of Cancer and Capricorn the precipitation is less than on either

side of this region, on account of downward air currents, as previously explained.

Due to evaporation from falling rain drops, precipitation appears to increase with altitude up to 3000 feet and then to decrease. This, however, does not hold for mountain regions. Wherever the air currents are off the ocean and upward motion is induced by the elevation of the land, precipitation increases with altitude to practically the highest ground elevations.

Regions near the ocean may have high or low precipitation, depending almost entirely upon whether the winds are off the ocean or off the land.

Irregular Occurrence in United States. — In the region of cyclonic precipitation which covers practically all of the United States east of the Rocky Mountains, great variations in rainfall are usual occurrences. On the whole, the greater the depth of precipitation in the path of the storm the smaller the area over which the precipitation extends.

A good conception of the irregular manner in which precipitation occurs can be secured from a study of Figs. 63 to 66 showing monthly precipitation in the United States for July, August and September, 1915. Were these maps prepared on a larger scale, still greater irregularities would be shown. Regions that have little rain one month, have considerable the next and *vice versa.*

For example, in July, the precipitation in southeastern Iowa was about 10 inches, in August it was less than 2 inches and in September it was between 6 and 8 inches. The region about St. Louis had between 6 and 8 inches of rain in July, over 10 inches in August and less than 2 inches in September. In August the precipitation varied from less than 2 inches at Keokuk, Iowa, to over 10 inches at St. Louis, Mo., about 150 miles distant, and from over 15 inches in southwestern Arkansas to less than 4 inches in the southeastern part of the same state. Other irregularities, equally great, are to be found elsewhere in the United States and in almost any month of any year.

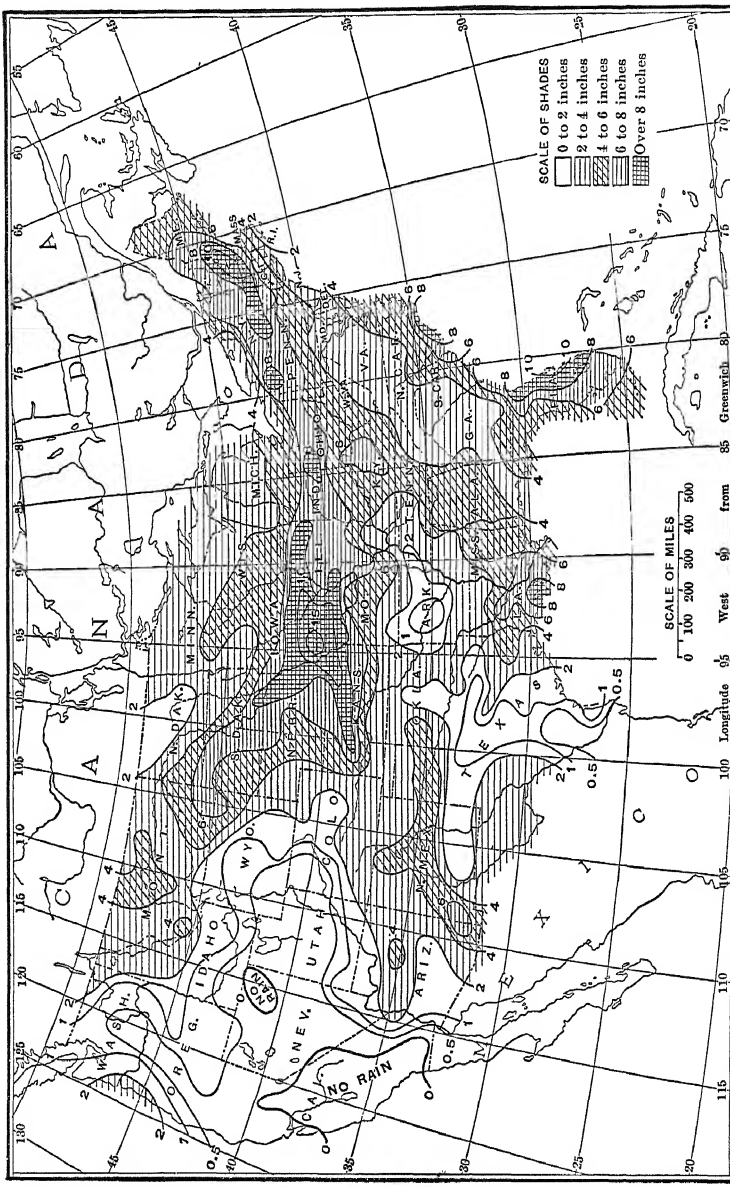


Fig. 63. — Precipitation in the United States during July, 1915.

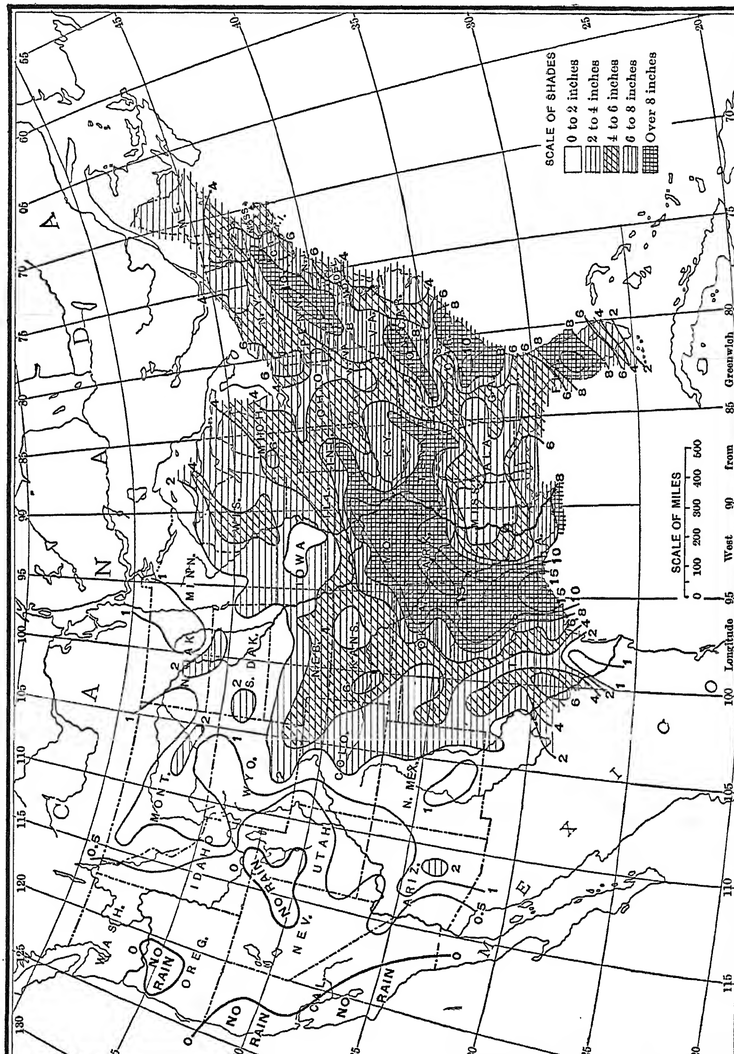


FIG. 64. — Precipitation in the United States during August, 1915.

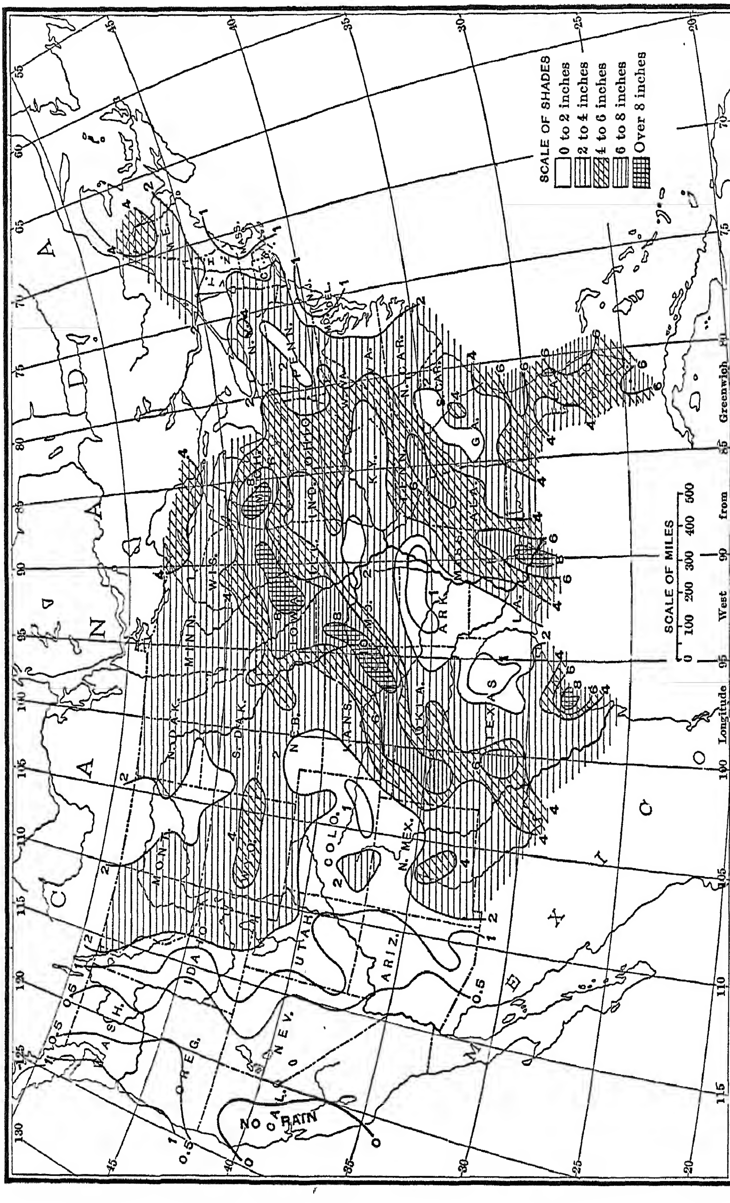


FIG. 65. — Precipitation in the United States during September, 1915.

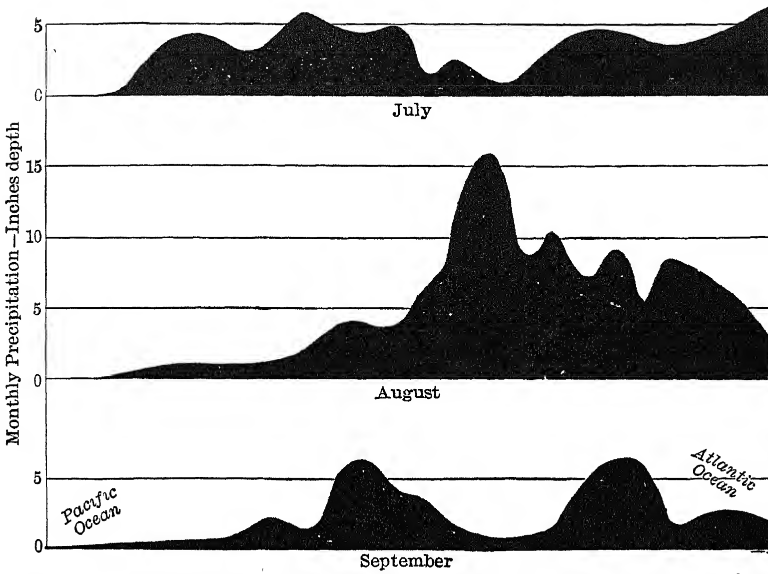


Fig. 66. — Profile along 35th Parallel showing Irregularity of Precipitation during July, August and September, 1915.

Mean Annual Precipitation. — The mean annual precipitation in the United States is shown in Fig. 67. As longer records become available, these averages may be changed somewhat. The annual precipitation at any given station varies considerably from year to year. Binnie * concluded that a thirty-year-mean would probably be in error about 2 per cent; a twenty-year mean $3\frac{1}{4}$ per cent; a ten-year mean $8\frac{1}{4}$ per cent; and a five-year mean might be in error 15 per cent.

Records of mean annual precipitation are not of much service, however, in the design of most works for the utilization or control of water. The runoff resulting from the average precipitation can seldom be utilized. Records of exceptionable conditions are of more importance, on the whole, than records of average conditions.

Cycles in Annual Precipitation. — Graphs of annual and progressive mean annual precipitation together with frequency

* Binnie, Sir Alexander, Rainfall, Reservoirs, and Water Supply, 1913, p. 10.

curves of annual precipitation at a number of long-term stations in the United States are shown in Figs. 68 to 105.

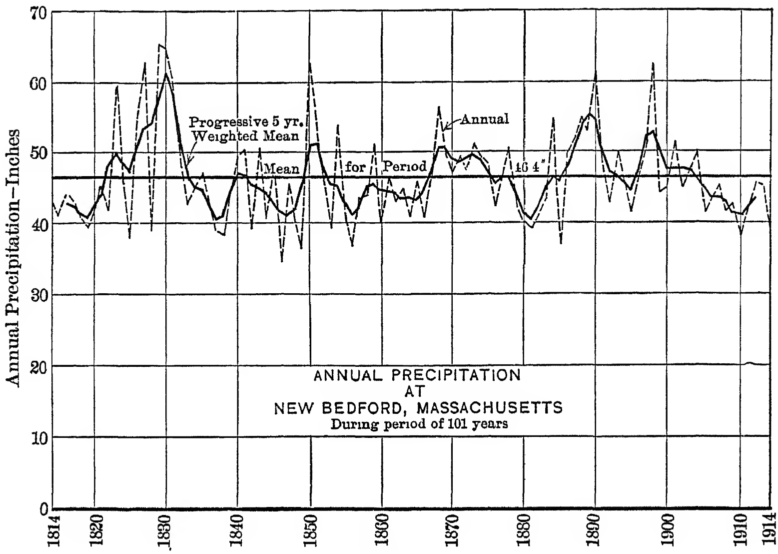


FIG. 68.

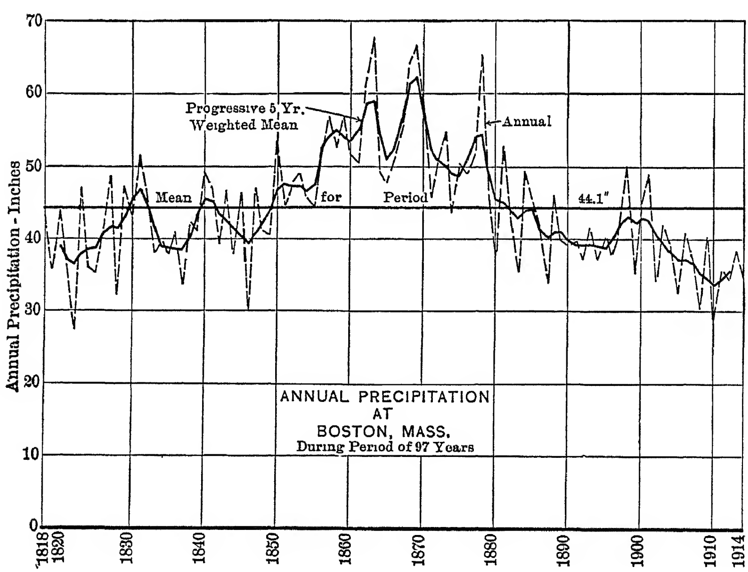
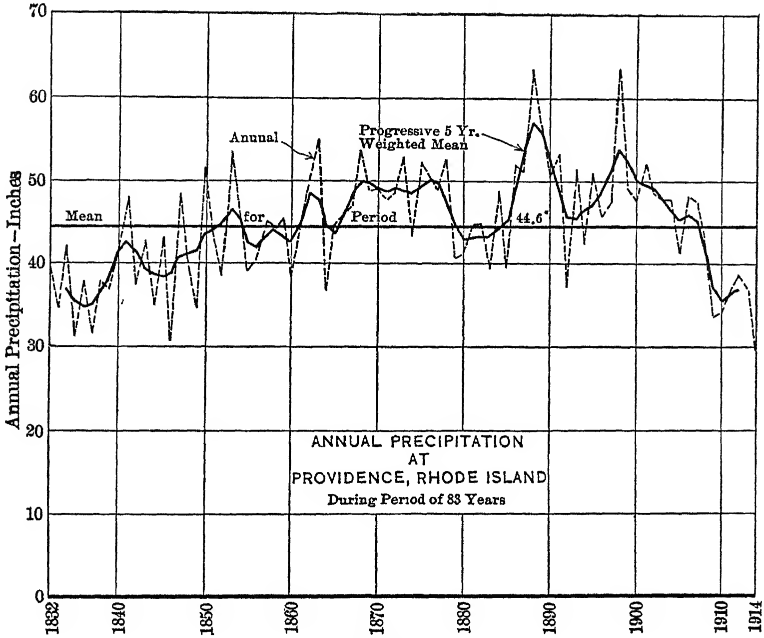
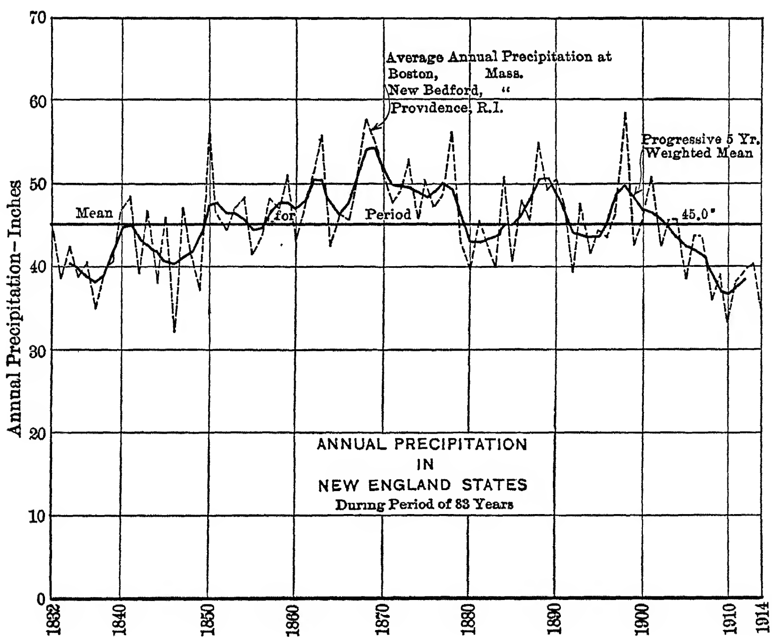


FIG. 69.



Annual
Progressive 5 Yr.
Weighted Mean
Mean for Period
44.6"
ANNUAL PRECIPITATION
AT
PROVIDENCE, RHODE ISLAND
During Period of 83 Years
Annual Precipitation-Inches
70
60
50
40
30
20
10
0
1832
1840
1850
1860
1870
1880
1890
1900
1910
1914

FIG. 70.



Average Annual Precipitation at
Boston, Mass.
New Bedford, "
Providence, R.I.
Progressive 5 Yr.
Weighted Mean
Mean for Period
45.0"
ANNUAL PRECIPITATION
IN
NEW ENGLAND STATES
During Period of 83 Years
Annual Precipitation-Inches
70
60
50
40
30
20
10
0
1832
1840
1850
1860
1870
1880
1890
1900
1910
1914

FIG. 71.

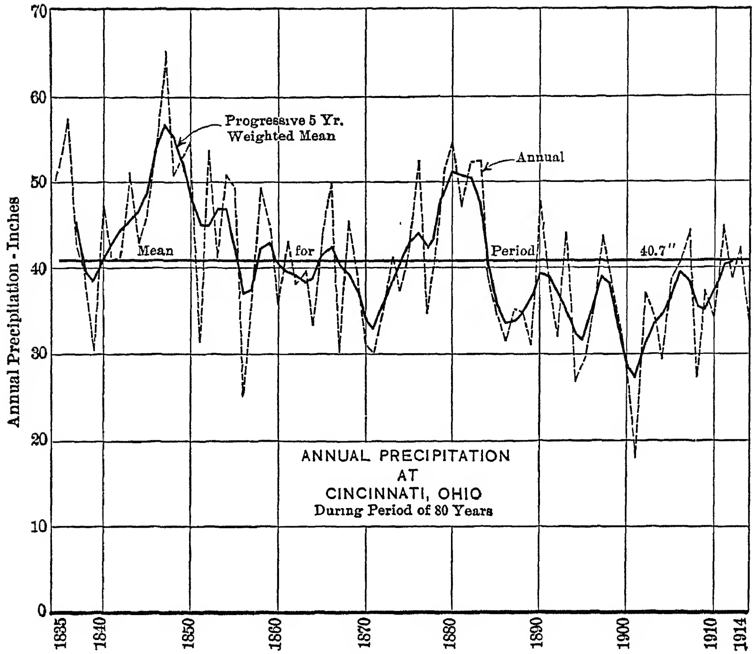

Annual Precipitation - Inches
Progressive 5 Yr. Weighted Mean
Annual
Mean for Period 40.7″
ANNUAL PRECIPITATION AT CINCINNATI, OHIO
During Period of 80 Years
1835
1840
1850
1860
1870
1880
1890
1900
1910
1914

FIG. 72.

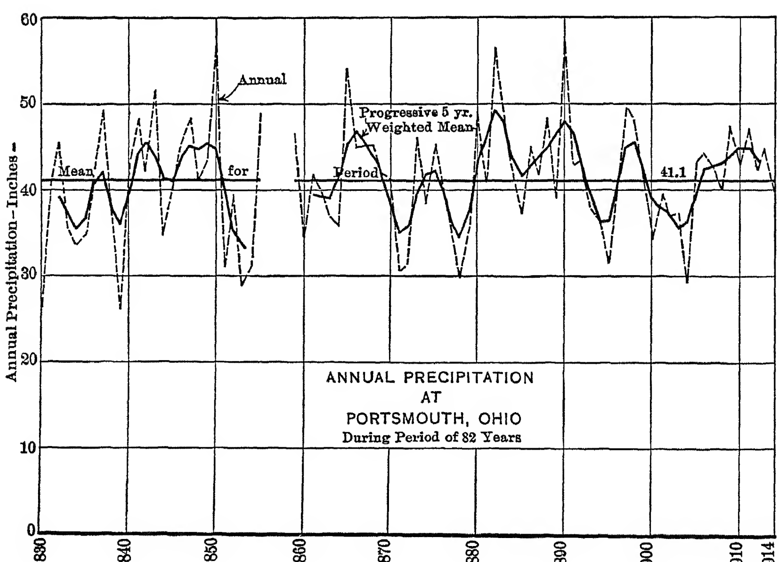

Annual Precipitation - Inches
Annual
Progressive 5 yr. Weighted Mean
Mean for Period 41.1
ANNUAL PRECIPITATION AT PORTSMOUTH, OHIO
During Period of 82 Years
1830
1840
1850
1860
1870
1880
1890
1900
1910
1914

FIG. 73.

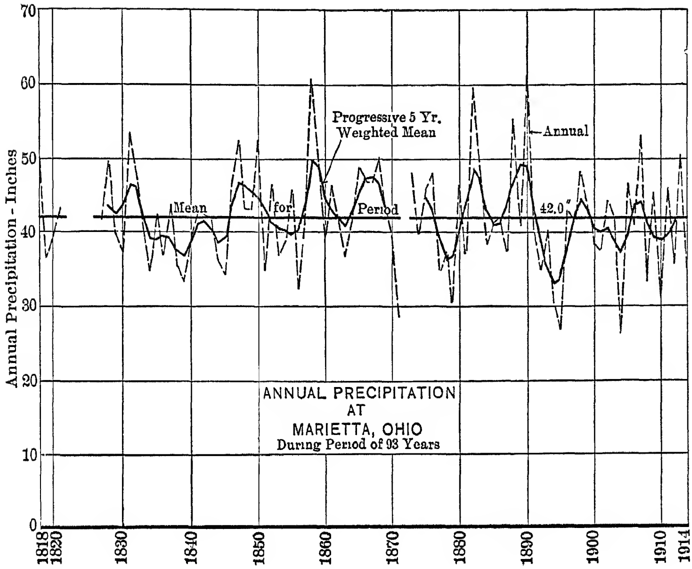

Progressive 5 Yr. Weighted Mean
Annual
Mean for Period 42.0"
ANNUAL PRECIPITATION AT MARIETTA, OHIO
During Period of 93 Years
Annual Precipitation - Inches
70
60
50
40
30
20
10
0
1818
1820
1830
1840
1850
1860
1870
1880
1890
1900
1910
1914

FIG. 74.

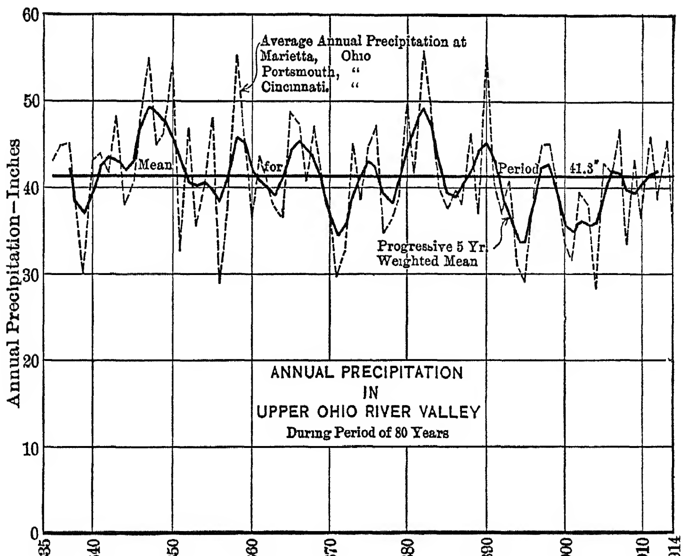

Average Annual Precipitation at
Marietta, Ohio
Portsmouth, "
Cincinnati. "
Mean for Period 41.3"
Progressive 5 Yr. Weighted Mean
ANNUAL PRECIPITATION IN UPPER OHIO RIVER VALLEY
During Period of 80 Years
Annual Precipitation—Inches
60
50
40
30
20
10
0
1835
1840
1850
1860
1870
1880
1890
1900
1910
1914

FIG. 75.

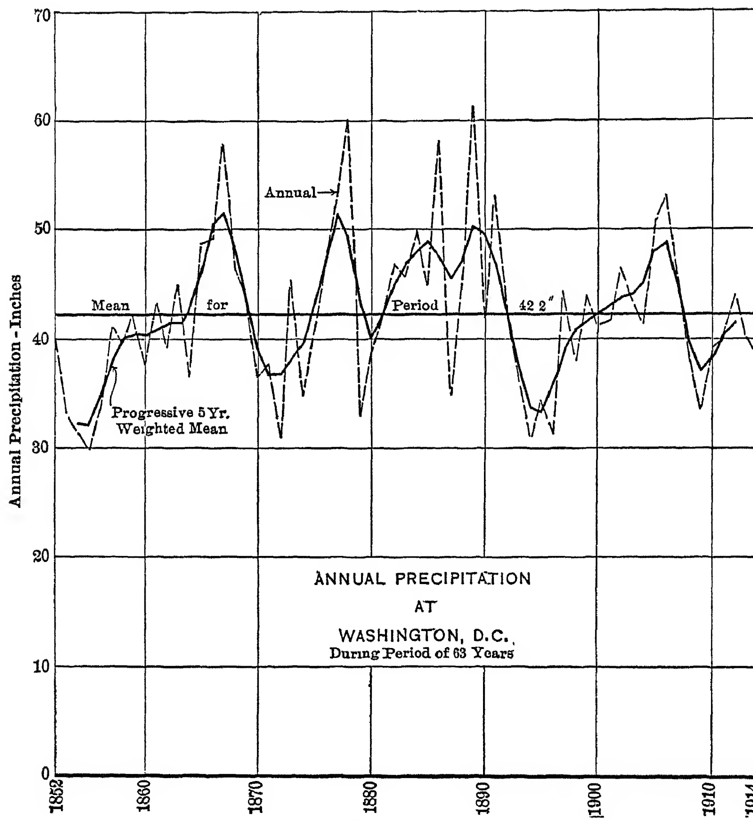

70
60
50
40
30
20
10
0
Annual Precipitation - Inches
Annual
Mean for Period 42 2″
Progressive 5 Yr. Weighted Mean
ANNUAL PRECIPITATION
AT
WASHINGTON, D.C.
During Period of 63 Years
1852
1860
1870
1880
1890
1900
1910
1914

FIG. 76.

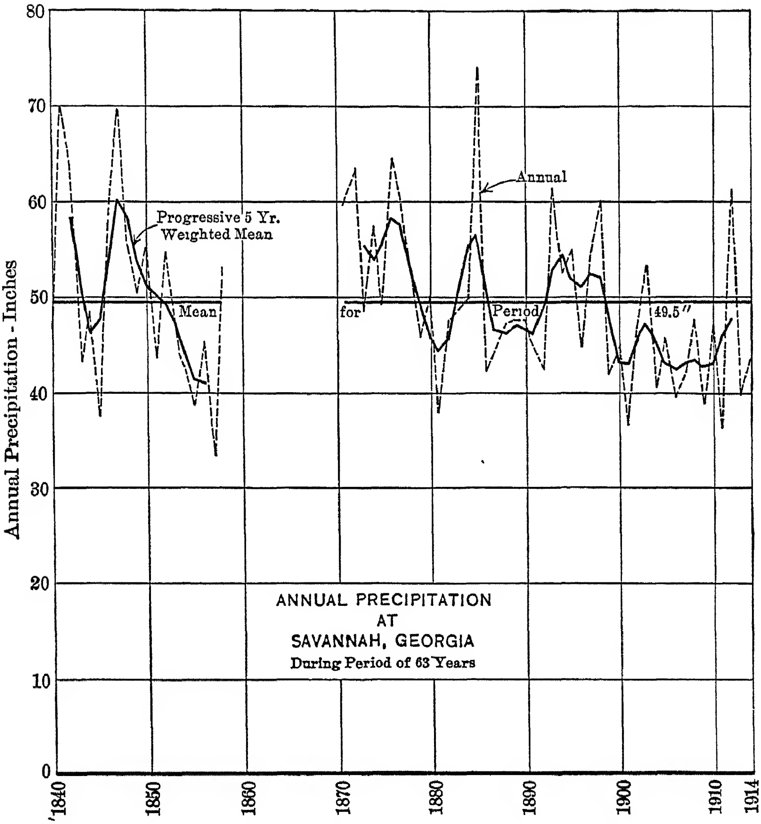

80
70
60
50
40
30
20
10
0
Annual Precipitation - Inches
1840
1850
1860
1870
1880
1890
1900
1910
1914
Progressive 5 Yr. Weighted Mean
Annual
Mean for Period 49.5″
ANNUAL PRECIPITATION
AT
SAVANNAH, GEORGIA
During Period of 63 Years

FIG. 77.

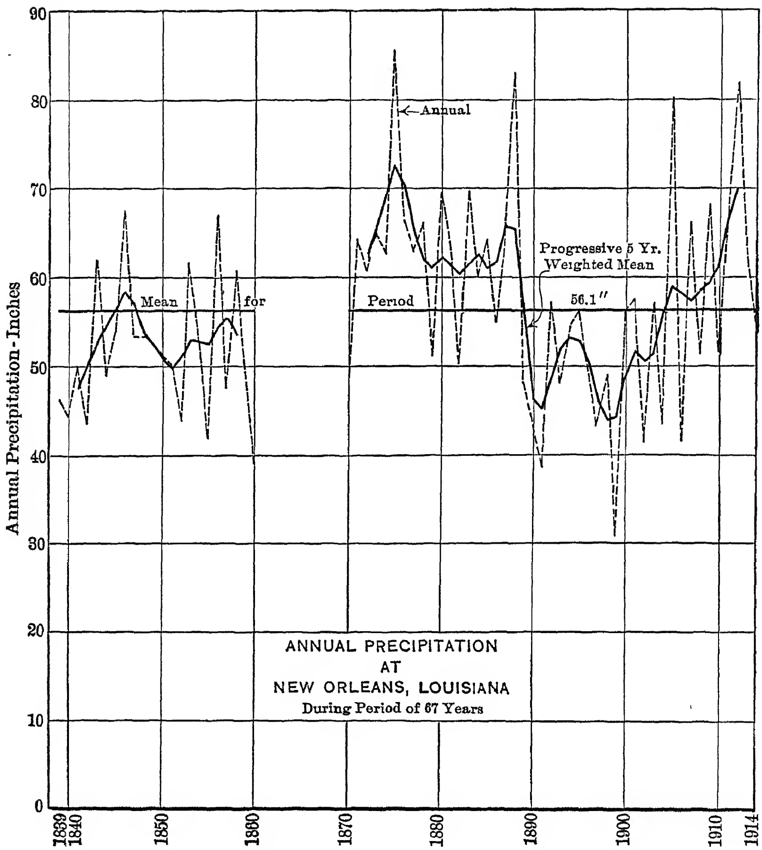

90
80
70
60
50
40
30
20
10
0
Annual Precipitation - Inches
Annual
Progressive 5 Yr. Weighted Mean
Mean for Period 56.1″
ANNUAL PRECIPITATION
AT
NEW ORLEANS, LOUISIANA
During Period of 67 Years
1839
1840
1850
1860
1870
1880
1890
1900
1910
1914

FIG. 78.

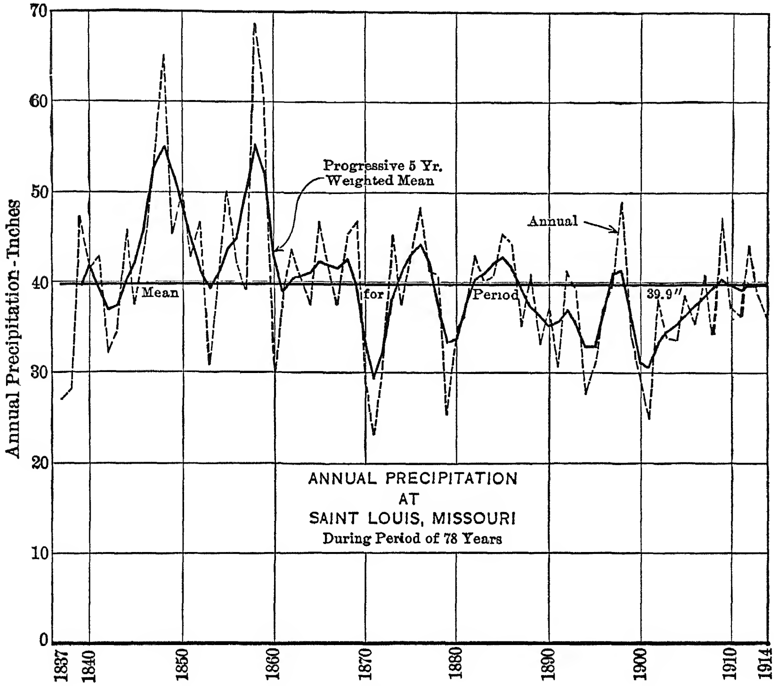

Annual Precipitation - Inches
70
60
50
40
30
20
10
0
Progressive 5 Yr. Weighted Mean
Annual
Mean for Period 39.9″
ANNUAL PRECIPITATION
AT
SAINT LOUIS, MISSOURI
During Period of 78 Years
1837
1840
1850
1860
1870
1880
1890
1900
1910
1914

FIG. 79.

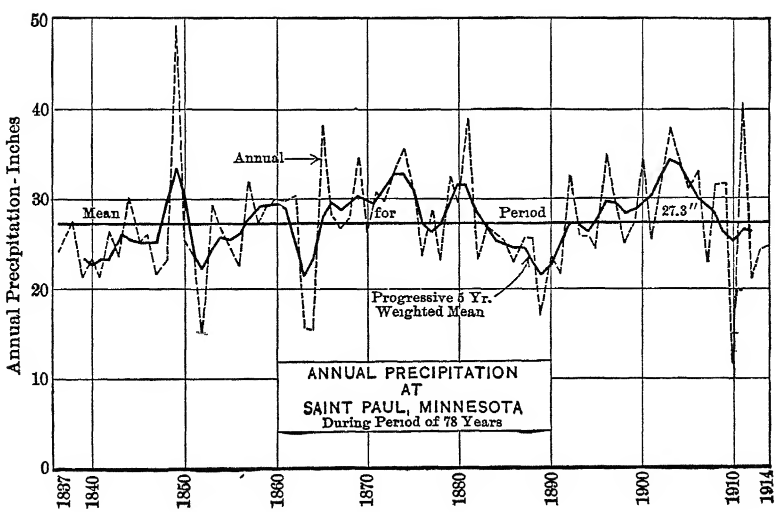

Annual Precipitation - Inches
50
40
30
20
10
0
Annual
Mean for Period 27.3″
Progressive 5 Yr. Weighted Mean
ANNUAL PRECIPITATION
AT
SAINT PAUL, MINNESOTA
During Period of 78 Years
1837
1840
1850
1860
1870
1880
1890
1900
1910
1914

FIG. 80.

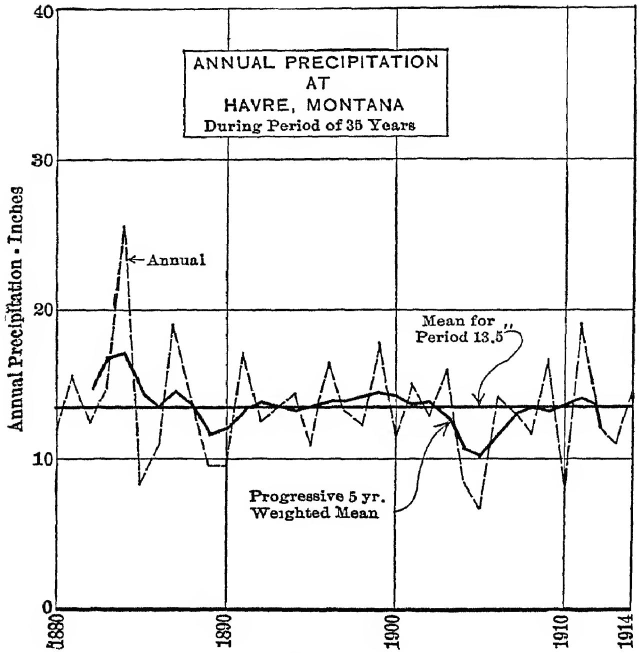

ANNUAL PRECIPITATION
AT
HAVRE, MONTANA
During Period of 35 Years
Annual
Mean for Period 13.5"
Progressive 5 yr. Weighted Mean
Annual Precipitation - Inches
40
30
20
10
0
1880
1890
1900
1910
1914

FIG. 81.

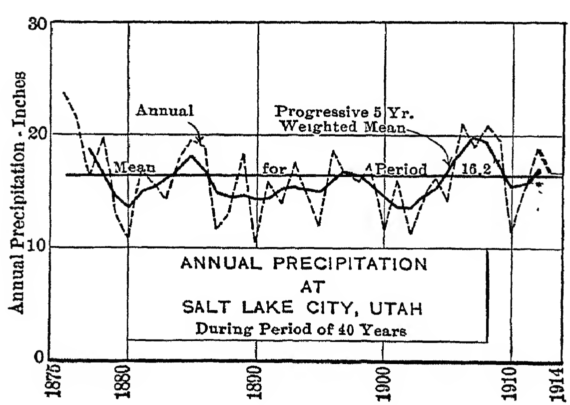

Annual
Progressive 5 Yr. Weighted Mean
Mean for Period 16.2
ANNUAL PRECIPITATION
AT
SALT LAKE CITY, UTAH
During Period of 40 Years
Annual Precipitation - Inches
30
20
10
0
1875
1880
1890
1900
1910
1914

FIG. 82.

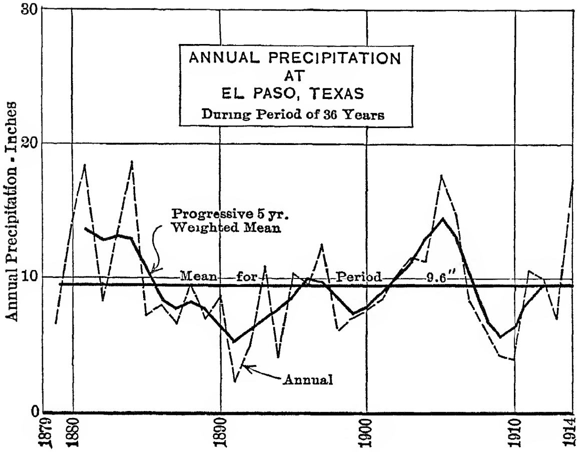


FIG. 83.

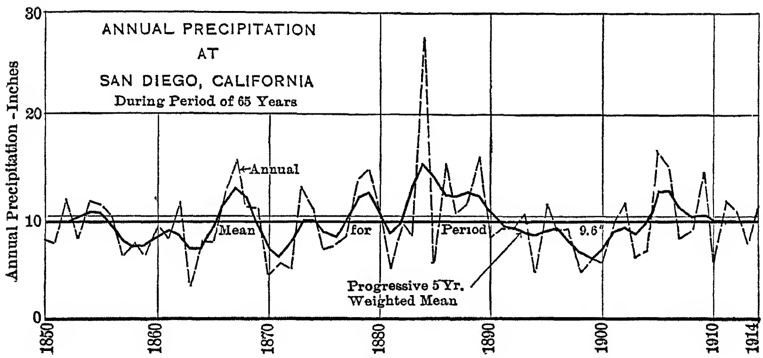


FIG. 84.

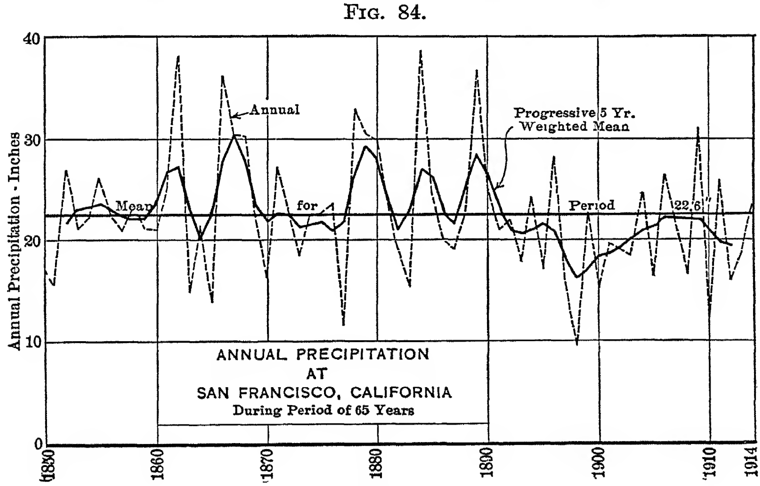


FIG. 85.

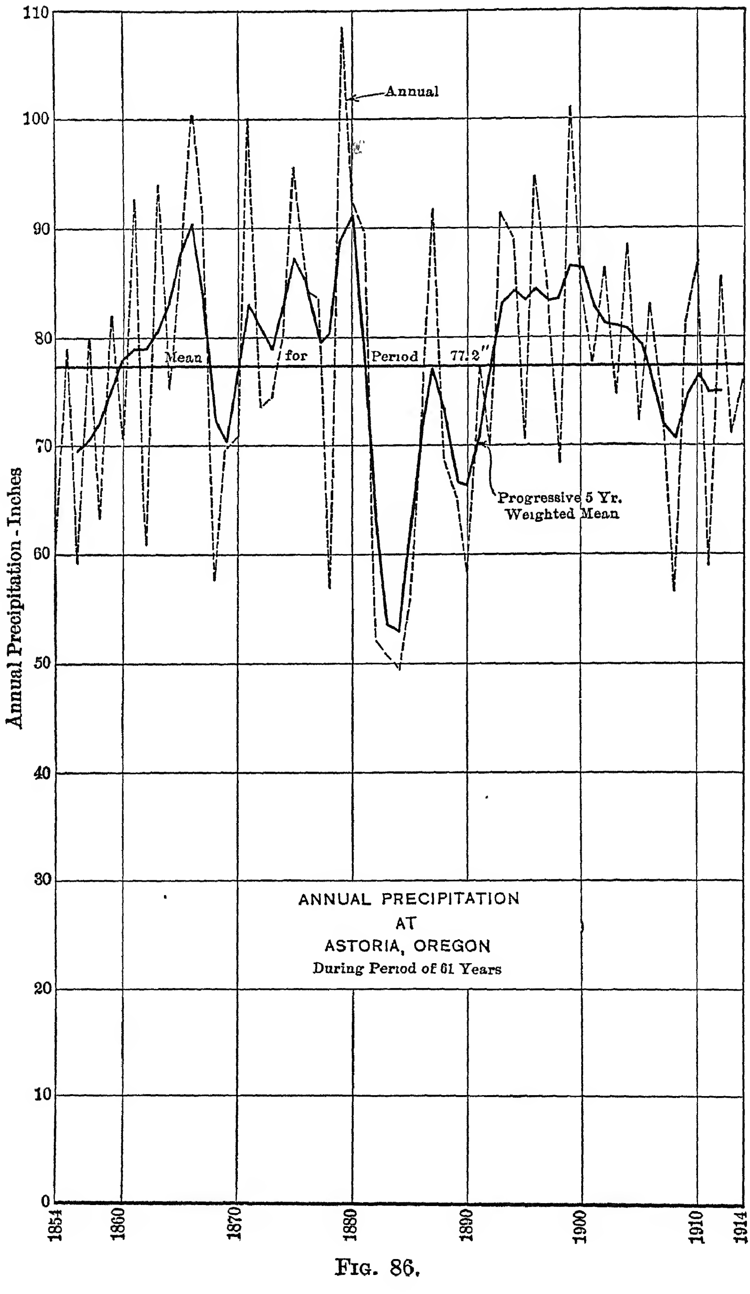

Annual
Mean for Period 77.2"
Progressive 5 Yr. Weighted Mean
ANNUAL PRECIPITATION
AT
ASTORIA, OREGON
During Period of 61 Years
Annual Precipitation - Inches
110
100
90
80
70
60
50
40
30
20
10
0
1854
1860
1870
1880
1890
1900
1910
1914

FIG. 86.

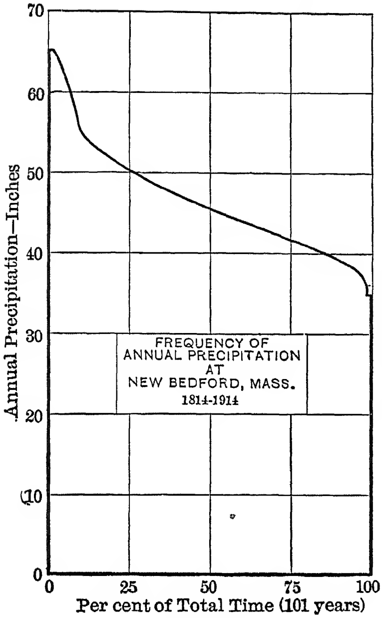


FIG. 87.

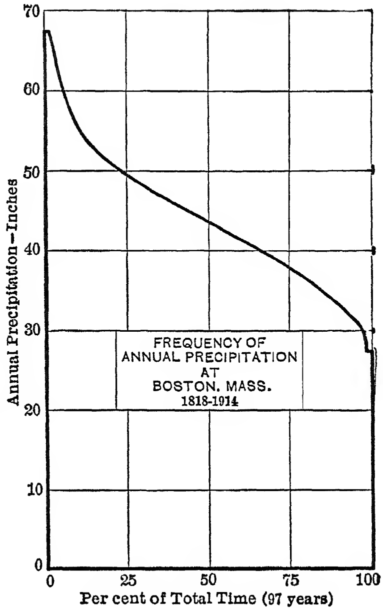


FIG. 88.

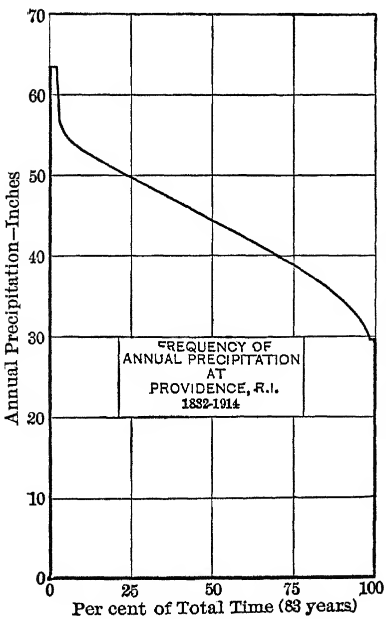


FIG. 89.

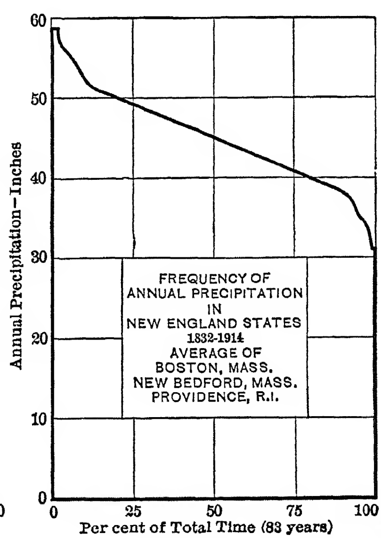


FIG. 90.

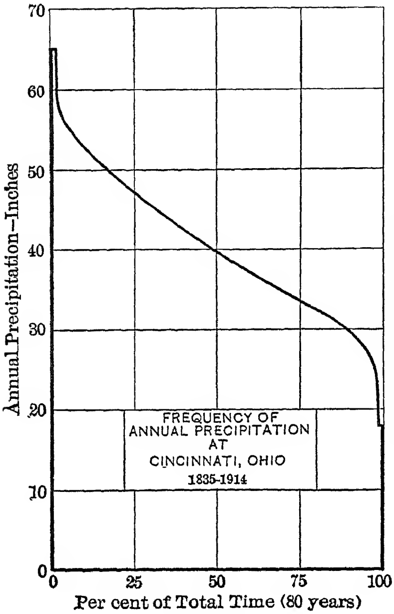


FIG. 91.

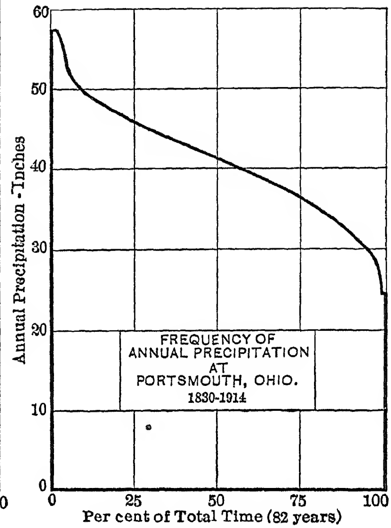


FIG. 92.

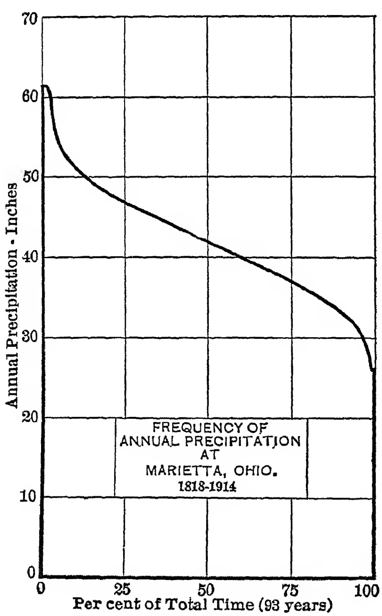


FIG. 93.

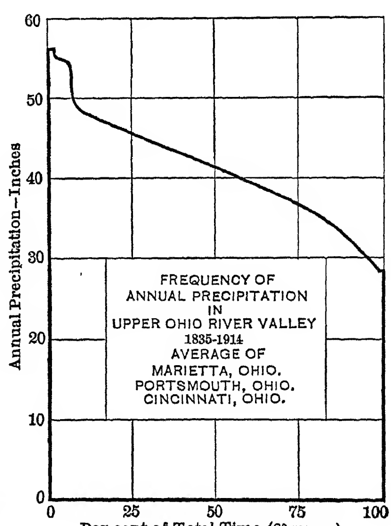


FIG. 94.

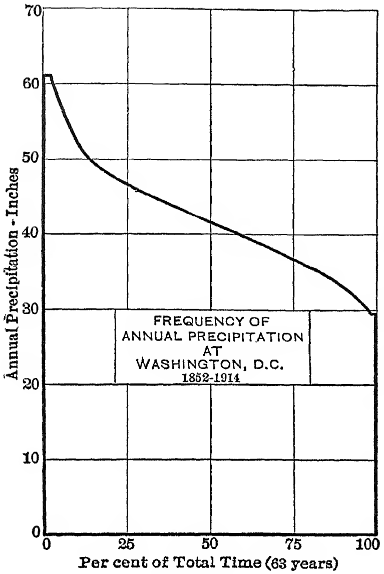


FIG. 95.

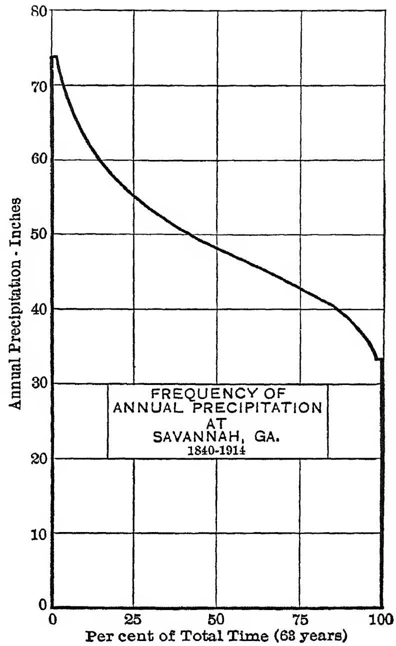


FIG. 96.

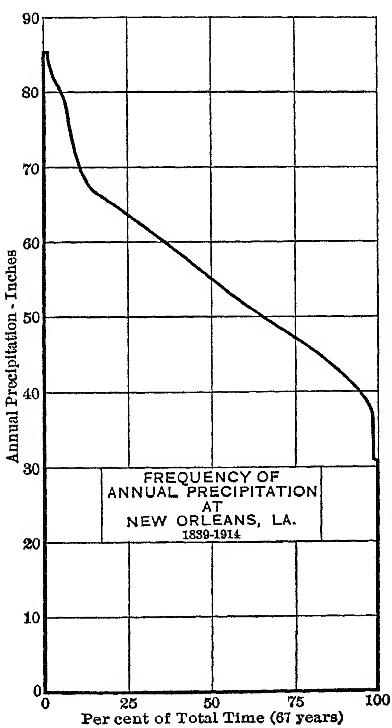


FIG. 97.

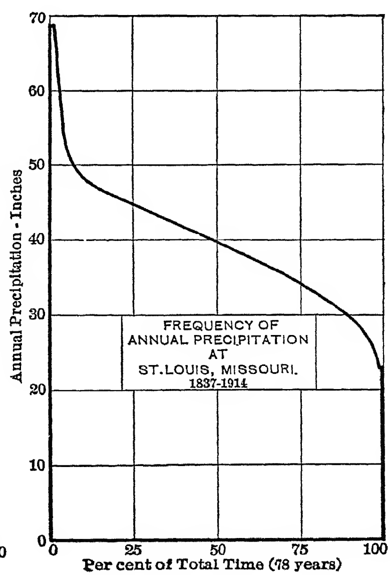


FIG. 98.

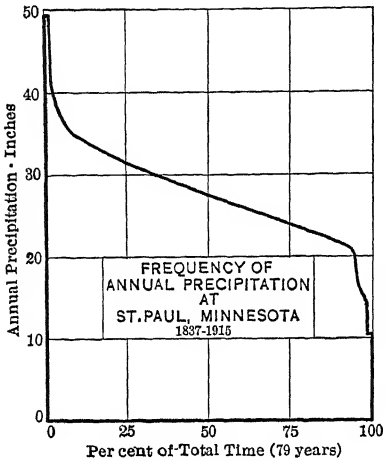


FIG. 99.

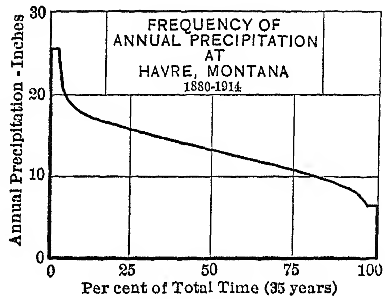


FIG. 100.

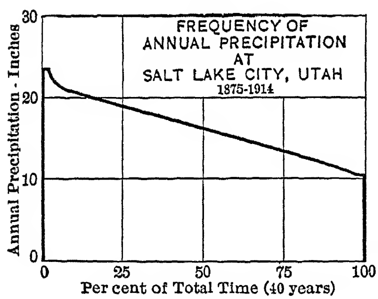


FIG. 101.

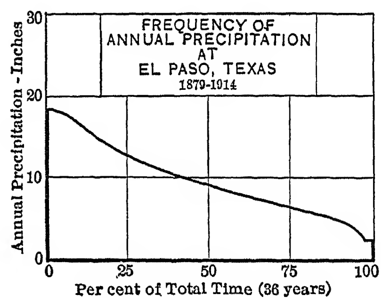


FIG. 102.

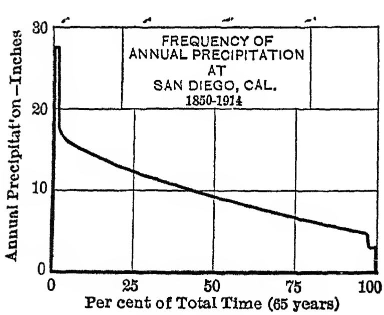


FIG. 103.

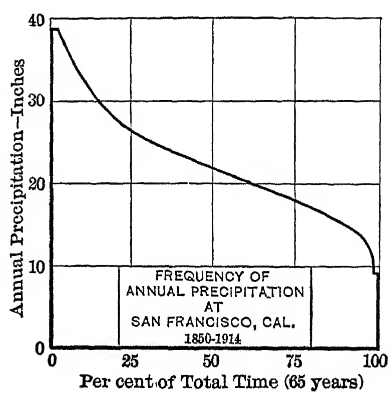


FIG. 104.

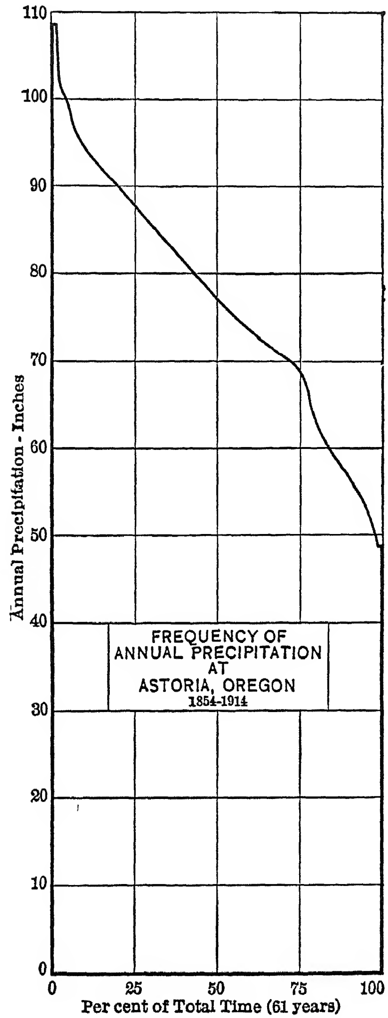


Fig. 105.

While attention has been called to the occurrence of natural phenomena in cycles, a study of variations in annual rainfall in the United States tends to indicate a lack of correlation between solar phenomena and precipitation.

If high and low annual precipitation occurred in synchronism with sun spots, one would expect to find the extremes of precipitation occurring simultaneously over large areas, at least, yet the graphs for Boston, New Bedford and Providence, stations which are relatively close together, show most striking divergence from the expected correspondence. The same conclusion holds with respect to the three Ohio River stations, Marietta, Portsmouth and Cincinnati.

A study of the graphs of Figs. 68 to 86 shows cycles of such irregular length, magnitude and diversity with respect to time as to lead one to believe that the amount of annual precipitation at any given observation station is a chance occurrence rather than the effect of a regularly-varying cause.*

Relation Between Length of Record and Extremes of Annual Precipitation. — Efforts to show a relation between length of record and maximum and minimum annual precipitation lead to erroneous conclusions. In general, it is, of course, true that the longer the term of years over which records extend, the higher the maximum and the lower the minimum. Exceptions, however, are about as frequent as the rule. This is well illustrated by the records for St. Paul, Minn., Cincinnati, Ohio, New Bedford, and Boston, Mass., graphically presented in Fig. 106. The recorded maximum annual precipitation at St. Paul, for example, occurred in the 13th year of the record and the minimum occurred in the 74th year of the record. Moreover, the 74th year minimum was only about two thirds of the minimum for the preceding 73 years. At St. Paul, New Bedford and Cincinnati, the maximum occurred near the beginning of the record. At Boston it occurred near the middle. At St. Paul and Cincinnati the minimum occurred near the

* Secular Variation of Precipitation is discussed by A. J. Henry in Bulletin D, Weather Bureau, 1897, p. 18.

See also "Group Distribution and Periodicity of Annual Rainfall Amounts" by Robert E. Horton, Cons. Engr., Albany, N. Y., in Monthly Weather Review, Oct., 1923, and article on correlation between solar and terrestrial phenomena by A. Streiff, Monthly Weather Review, July, 1926.

end of the record. At New Bedford and Boston it occurred near the beginning.

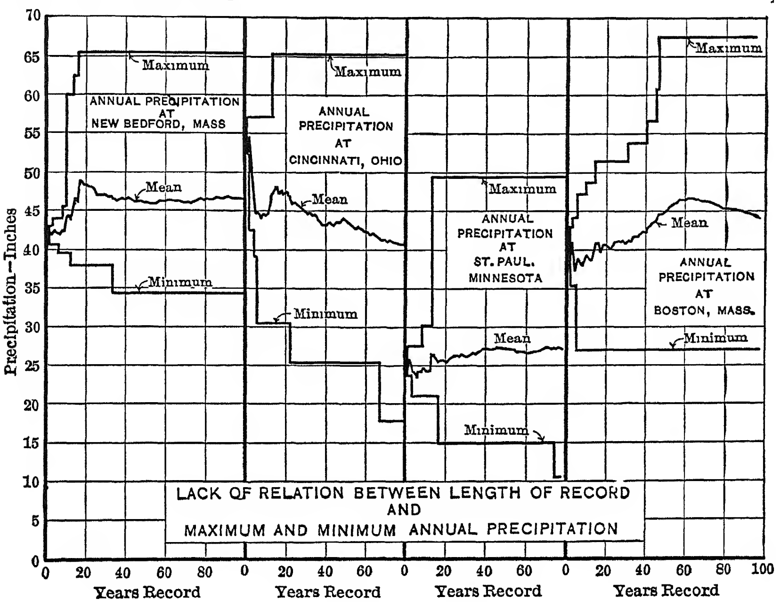


FIG. 106.

Map of Probable Extremes of Annual Precipitation in United States. — In view of this lack of relation between length of record and probable maximum and minimum annual precipitation in different regions, the author made a study of all the records of annual precipitation available for the United States up to and including the year 1914. The maximum and the minimum for each station were selected, and with these as a basis, maps of probable maximum and minimum annual precipitation, Figs. 107 and 108, were prepared. The extremes in any given locality were given most weight and isolated records that clearly conflicted with these were disregarded. While the records in no case extend over a longer period than 101 years, it is probable that the limits of annual rainfall indicated on this map will not be exceeded at any one station in the eastern half of the United States with a greater frequency than once in several hundred years.

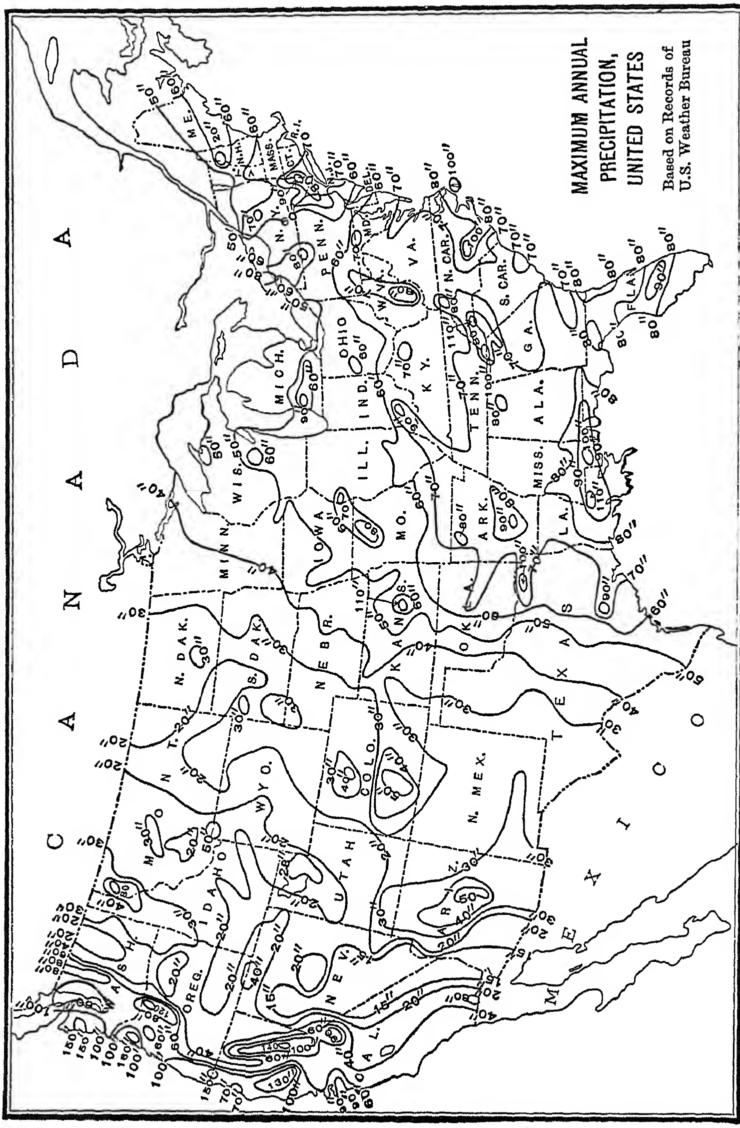

MAXIMUM ANNUAL
PRECIPITATION,
UNITED STATES
Based on Records of
U.S. Weather Bureau
CANADA
MEXICO

FIG. 107.

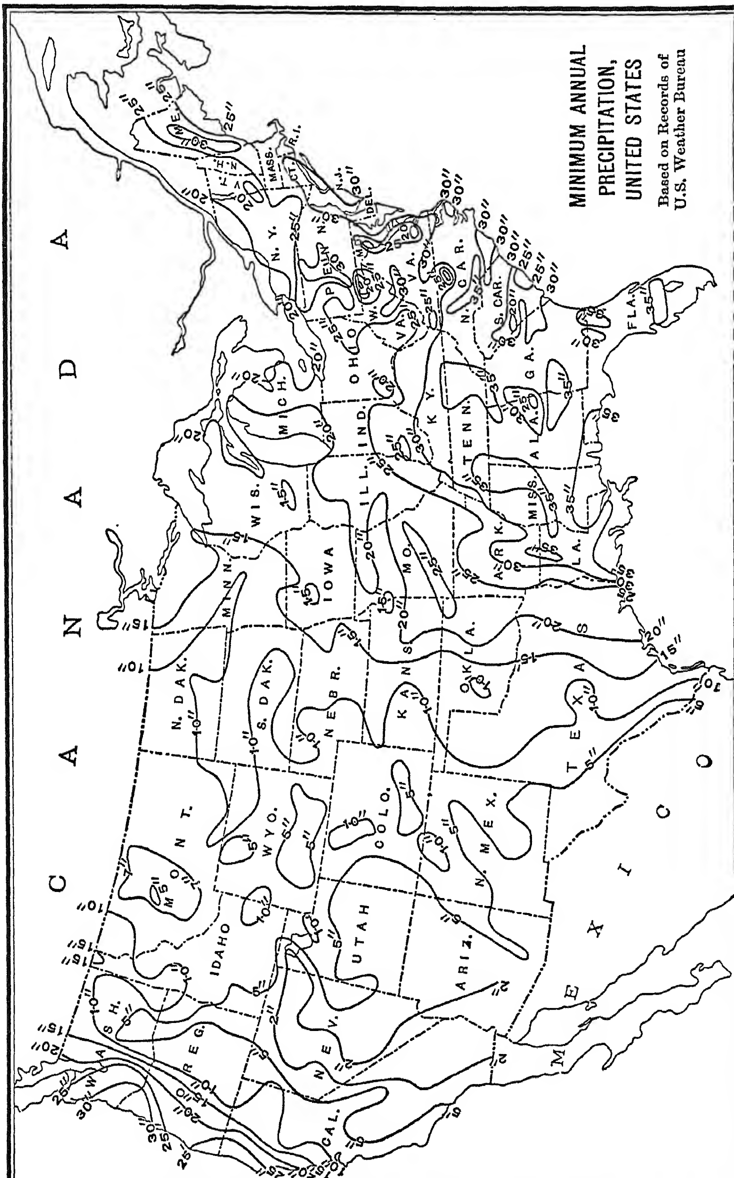

MINIMUM ANNUAL
PRECIPITATION,
UNITED STATES
Based on Records of
U.S. Weather Bureau
C A N A D A
M E X I C O

Fig. 108.

Monthly Precipitation. — The shorter the unit of time, the greater the diversity in amount of precipitation which may be expected in the given time. The curves of Figs. 109 to 120 show the maximum, minimum and mean monthly precipitation; the precipitation for each month of the wettest year and of the driest year, together with frequency curves of monthly

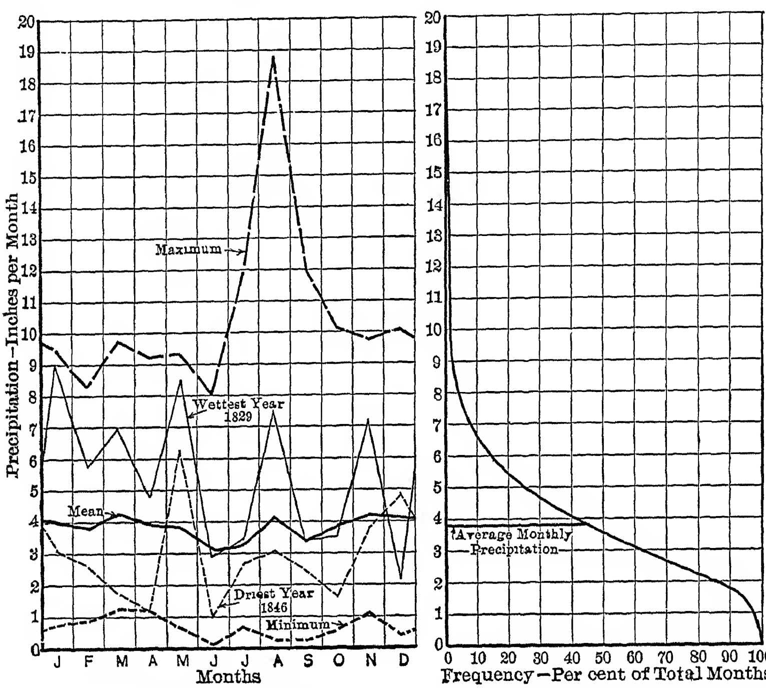


FIG. 109. — Monthly Precipitation at New Bedford, Mass. Records of 101 years.

precipitation, at typical stations in the United States, based on the records of the U. S. Weather Bureau, to 1914 incl. The average monthly precipitation has been added to the frequency curve, and it is interesting to note that the monthly precipitation is above the average for about 40 per cent of the time and below the average for about 60 per cent of the time. This fact raises the question of whether the use of the average precipitation as the "normal" is justifiable.

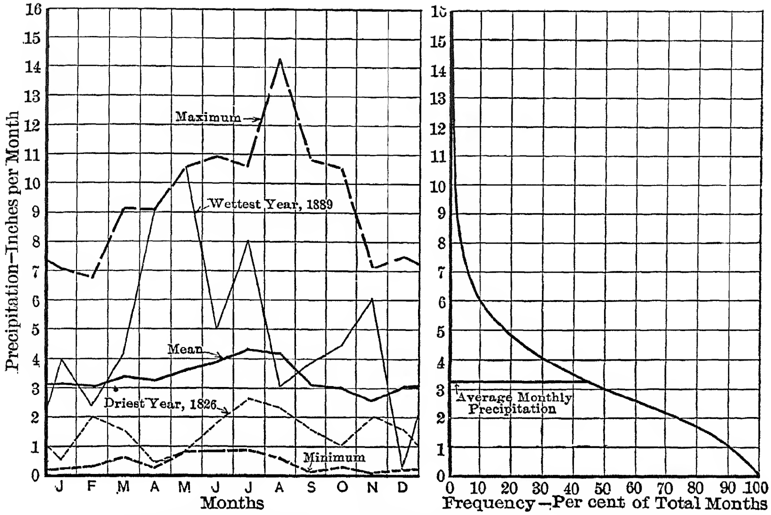


FIG. 110.—Monthly Precipitation at Washington, D. C. Records of 77 years.

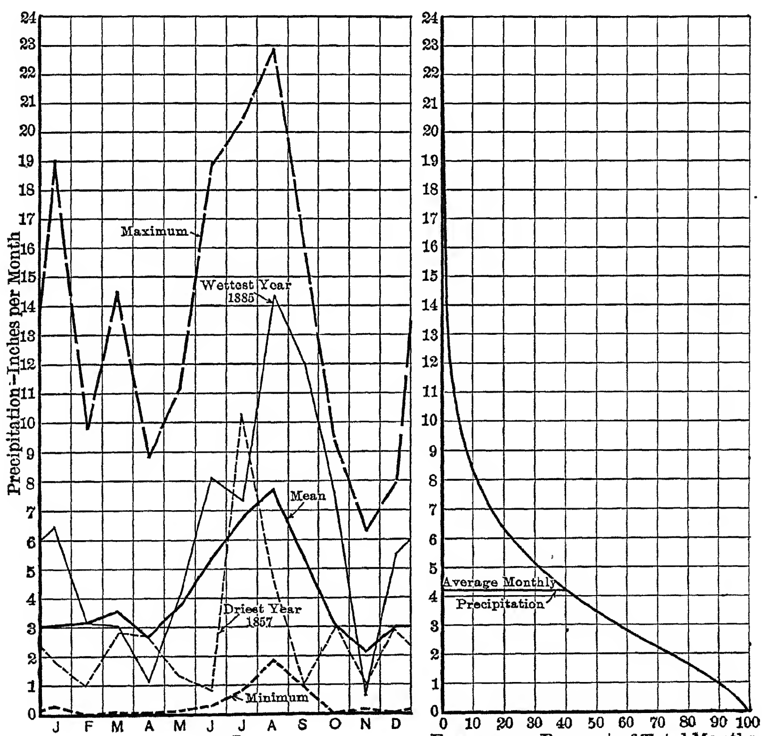


FIG. 111.—Monthly Precipitation at Savannah, Georgia. Records of 66 years.

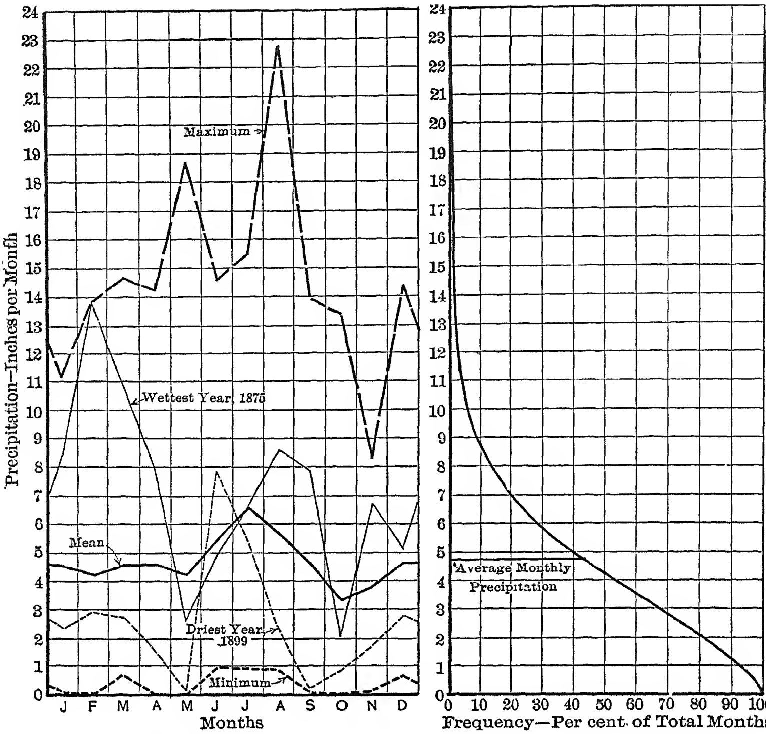


FIG. 112. — Monthly Precipitation at New Orleans, La. Records of 70 years.

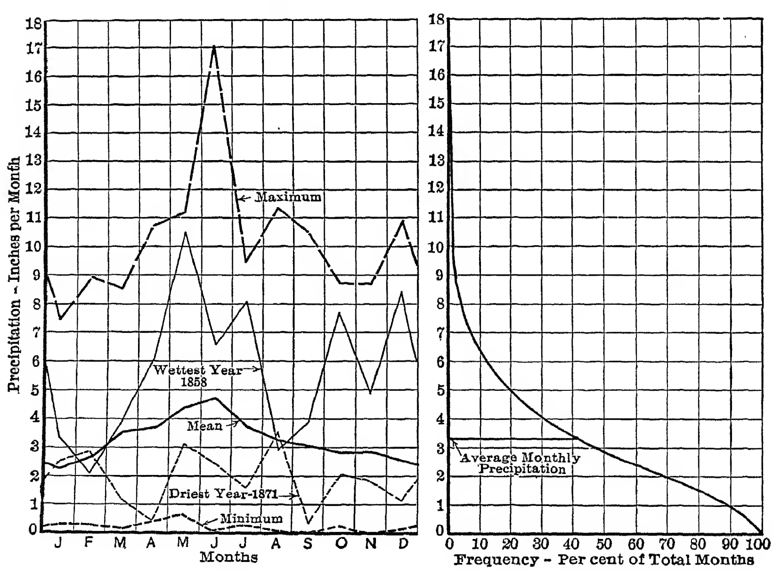


FIG. 113. — Monthly Precipitation at St. Louis, Mo. Records of 70 years.

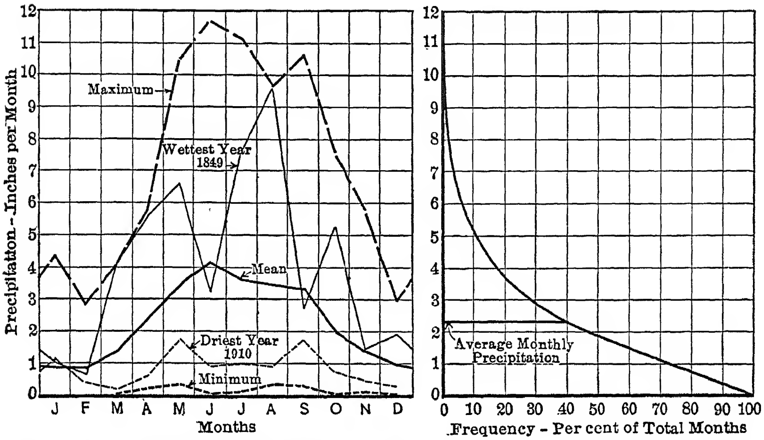


FIG. 114. — Monthly Precipitation at St. Paul, Minn. Records of 79 years.

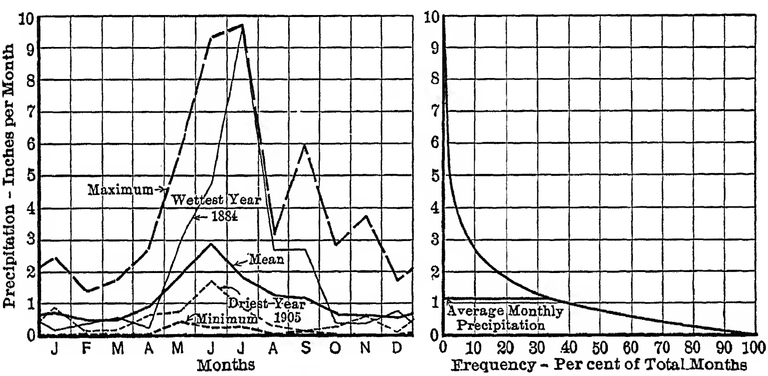


FIG. 115. — Monthly Precipitation at Havre, Montana. Records of 36 years.

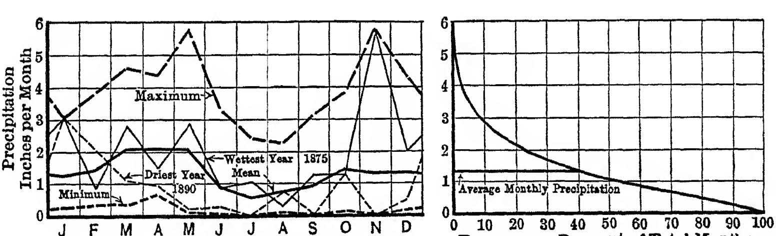


FIG. 116. — Monthly Precipitation at Salt Lake City, Utah. Records of 42 years.

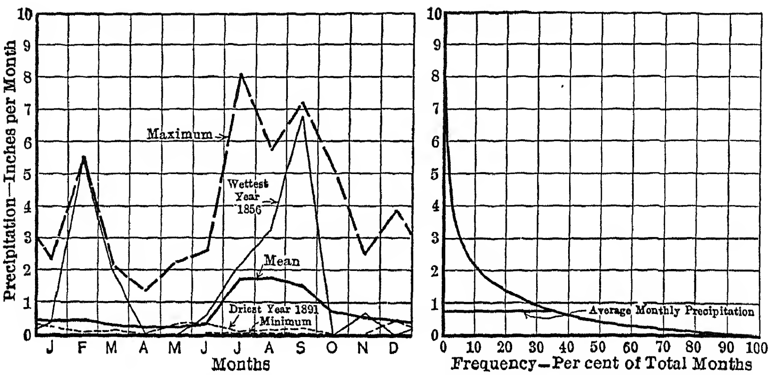


FIG. 117. — Monthly Precipitation at El Paso, Texas. Records of 53 years.

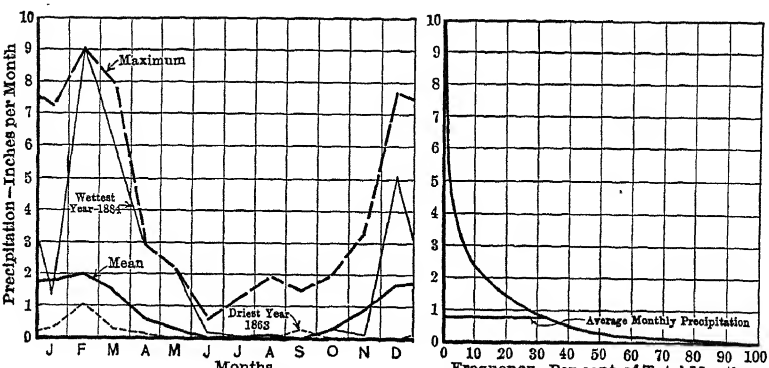


FIG. 118. — Monthly Precipitation at San Diego, Calif. Records of 66 years.

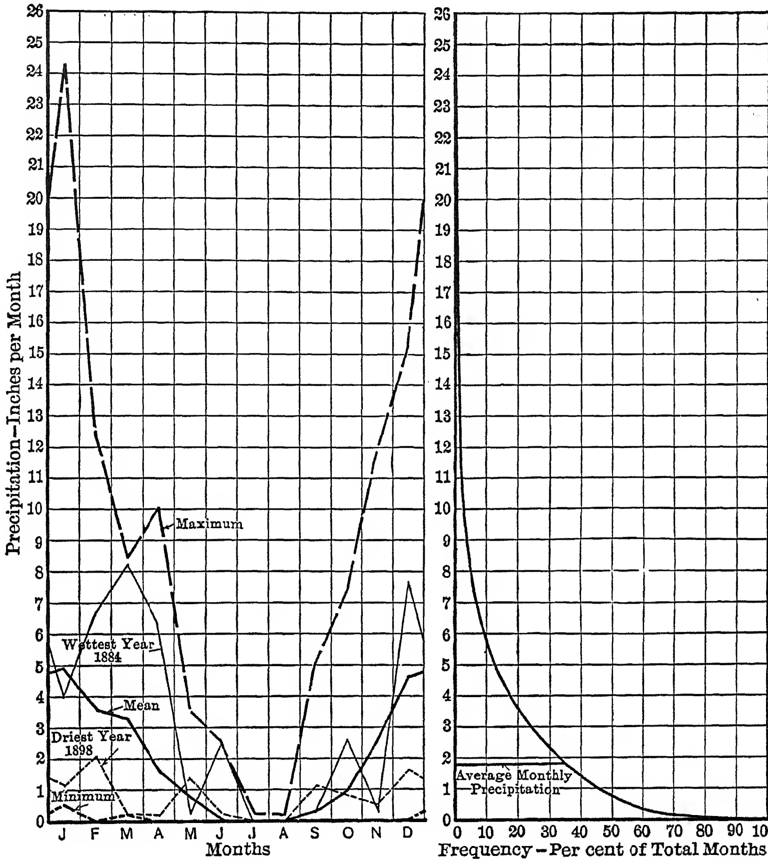


FIG. 119. — Monthly Precipitation at San Francisco, Cal. Records of 66 years.

Webster's International Dictionary defines "normal" as the "ordinary or usual condition, degree, quantity or the like; average; mean." It is apparent that the average or mean monthly precipitation is not, by any means, "the ordinary or usual" monthly rainfall. The difficulty with the application of this definition lies in the fact that identical recurrences of natural phenomena are extremely rare. However, the amount of precipitation which occurs most frequently in any given period of time would appear to best meet the condition imposed by the definition.

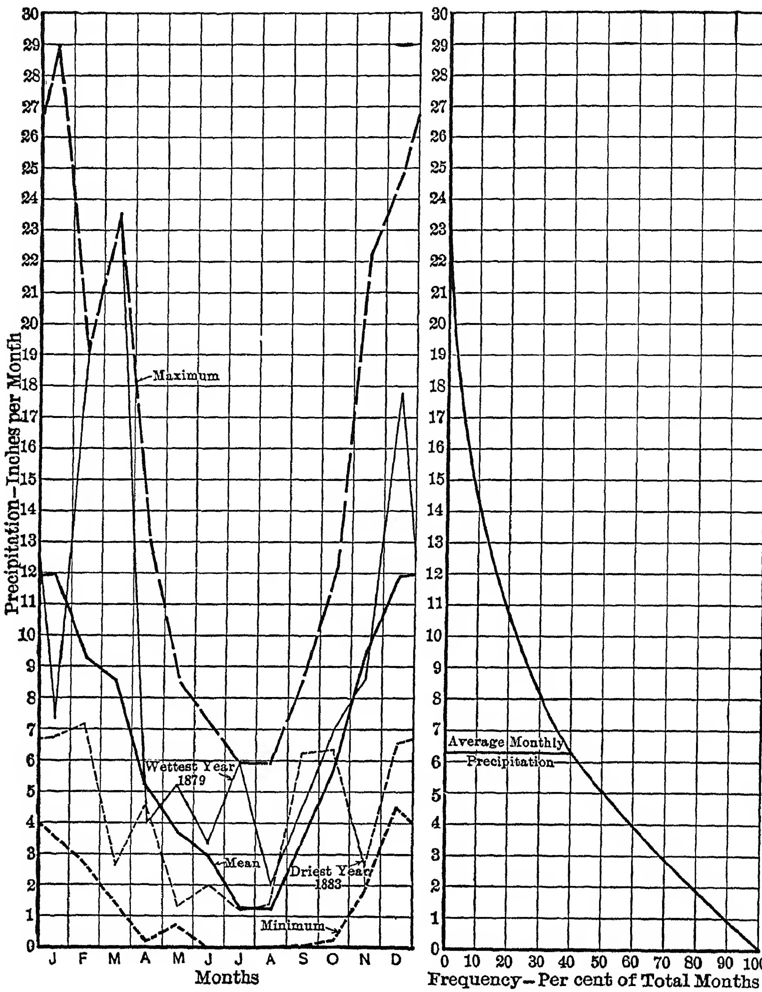


FIG. 120. — Monthly Precipitation at Astoria, Oregon. Records of 62 years.

It would seem that the normal condition is that which prevails the greatest portion of the time, whether the phenomena be annual, monthly or daily precipitation, or lake or river stage. The "normal," according to this definition, can usually be readily determined from the frequency curve by noting the point of inflection. On some of the curves the change of curvature is so

gradual, however, that the point of inflection cannot readily be ascertained.

If more than one half the total number of months over which records extend, have no rainfall, for example, then the normal condition is zero monthly rainfall, though the average may still be one or two inches or more. The normal rainfall during months when any rainfall occurs would, of course, be a quantity of some magnitude.

Determination of True Monthly Mean. — A map of the greatest recorded monthly rainfall in Minnesota is shown in Fig. 121. A variation in rainfall from less than 2 inches in the northwest corner of the State, to more than 14 inches in the southeast corner, will be noted, notwithstanding the generally heavy precipitation over the whole State.

When an accurate mean rainfall over an area such as the State of Minnesota is desired, it is necessary to determine the average precipitation from an isohyetal map such as Fig. 121. The mean derived from a simple average of the observed quantities at the different stations, as published by the Weather Bureau, gives 8.34 inches. By determining the true mean from the map, the low precipitation over the northeastern part of the State, in which relatively few observation stations are located, receives its proper weight and the mean is reduced to 7.57 inches.*

Excessive Monthly and Daily Precipitation. — Fig. 122 is a summary of the results of a study of the records of daily and monthly precipitation in Minnesota, Ohio, Kansas and Alabama. The frequency of occurrence of both daily and monthly precipitation was worked up on large-scale logarithmic cross-section paper, and merely a summary of the results is presented. The base data, upon which the conclusions of Fig. 122 are based, are sum-

* Methods of estimating the average rainfall on a drainage basin have been fully discussed by Robert E. Horton in Eng. News-Record, Aug. 2, 1917, p. 211, Monthly Weather Review, June and July, 1923, and Journal of New England Water Works Association, March, 1924.

Rainfall Interpolation is discussed by Robert E. Horton in Monthly Weather Review, June, 1923.

marized in Tables 4 and 5. As the number of stations per unit area varied somewhat in the different states, the data were reduced to the basis of one rainfall station for each 500 square miles. For example, in eastern Kansas, there was one station for each 643 square miles. The number of recorded daily rainfalls of all mag-

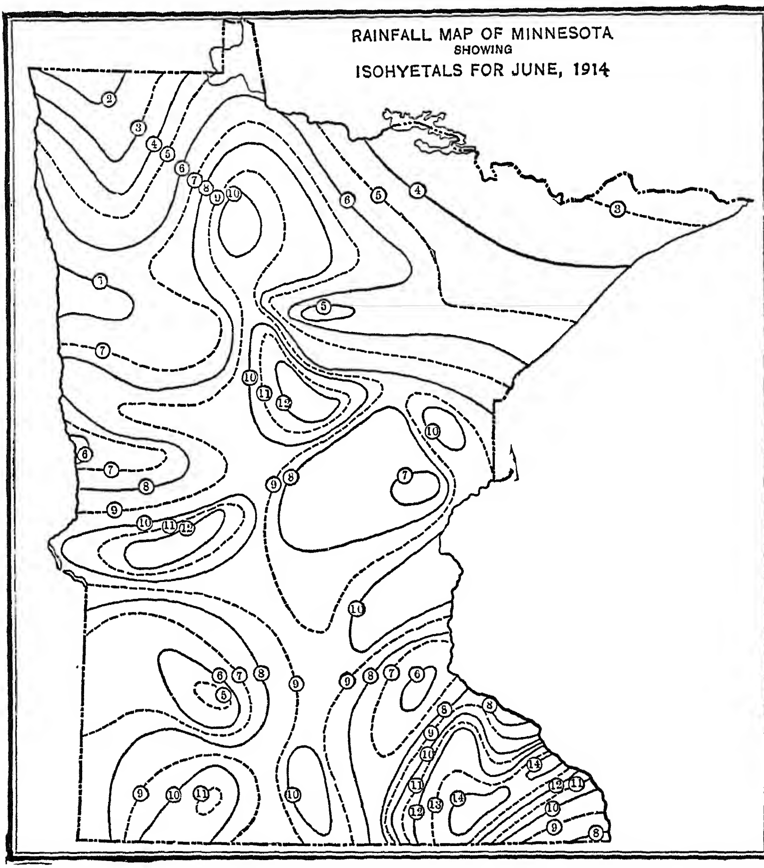


FIG. 121.

nitudes in this section of the State was increased in the ratio of 643 to 500 for the purpose of reducing the observed precipitation to the equivalent of one rainfall station for every 500 square miles.

Miami Rainfall Studies. — Similar but more exhaustive studies were later made by the Miami Conservancy District and pub-

lished in, "Storm Rainfall of Eastern United States, Technical Reports, Part V, Dayton, Ohio, 1917." The conclusions are summarized on pages 143 to 151 in the form of "Isopluvial Charts" reproduced from this publication. From the charts the amount of precipitation which may be expected once in 15, 50

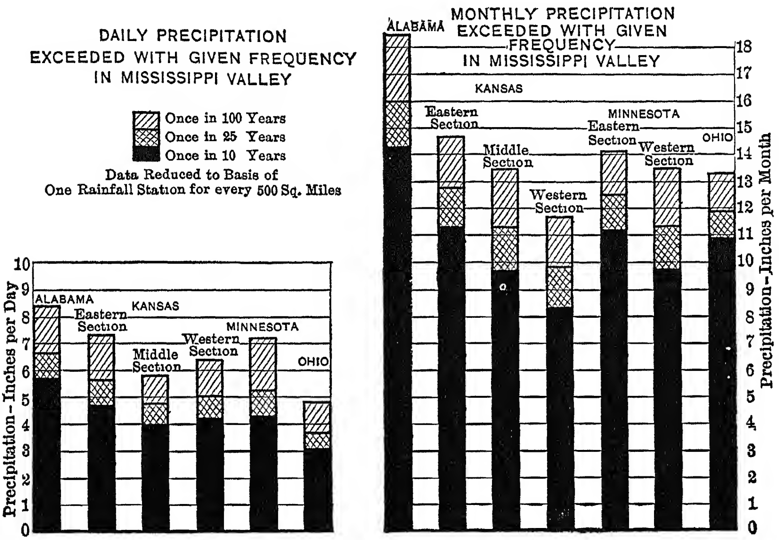


FIG. 122.

or 100 years during periods of one, two, three, four, five or six days, in any part of the United States east of the 103rd meridian, may be readily determined.

It is of interest to note that on page 66 of the publication referred to the statement is made that it would have been better to have fixed arbitrary values of rainfall for the several periods of time above which the rainfall was considered excessive than to have fixed the limiting values as a percentage of annual rainfall. The suggested procedure is exactly what the author had previously done in his rainfall studies presented on pages 124–128, and pages 164–175.

The maximum expected precipitation for one day, shown on the Miami charts, refers to the calendar day and not to maximum 24-hour amounts.

TABLE 4. — RECORDS OF EXCESSIVE DAILY PRECIPITATION

State of Minnesota

72 stations — 1180 square miles per station

Year	Number of days with given daily precipitation — inches depth														Total days
	1 00 to 1 24	1 25 to 1 49	1 50 to 1 74	1 75 to 1 99	2 00 to 2 49	2 50 to 2 99	3 00 to 3.99	4 00 to 4 99	5 00 to 5 99	6 00 to 6 99	7 00 to 7 99	8 00 to 8 99	9 00 to 9 99	10 00 to 10 99	
*1895	89	42	35	19	31	11	13	3	0	0	1	0	0	0	244
1896	162	69	57	35	43	15	15	3	0	1	0	0	0	0	400
1897	123	51	46	20	29	18	18	3	1	0	0	0	0	0	309
1898	102	63	39	23	29	8	10	1	0	0	1	0	0	0	276
1899	139	86	50	37	50	20	17	4	2	0	0	1	0	0	406
1900	162	81	60	41	52	26	21	13	2	0	0	0	0	0	458
1901	124	63	46	31	34	17	13	1	1	1	0	0	0	0	331
1902	138	69	61	41	44	12	10	5	1	0	0	0	0	0	381
1903	173	89	71	30	50	21	16	10	1	0	0	0	0	0	461
1904	123	66	39	20	31	10	3	1	0	0	0	0	0	0	293
1905	202	102	64	47	62	10	14	0	0	0	0	0	0	0	501
1906	157	75	63	28	40	9	10	3	0	1	0	0	0	0	386
1907	127	62	44	43	46	15	7	1	0	2	0	0	0	0	347
1908	199	107	109	47	36	10	8	5	2	0	0	0	0	0	525
1909	173	89	51	33	44	17	17	3	0	0	0	0	0	2	427
1910	83	33	14	5	9	5	1	0	0	0	0	0	0	0	150
1911	150	82	59	30	40	21	12	2	0	1	0	0	0	0	397
1912	130	65	40	28	20	8	6	3	0	0	1	0	0	0	301
1913	147	113	62	37	33	11	9	1	0	0	0	1	0	0	414
1914	220	116	93	41	47	16	18	3	1	0	0	0	0	0	555
1915	180	102	79	38	39	17	7	1	0	0	0	0	0	0	463
Total	3103	1625	1182	674	809	297	245	66	11	6	3	2	0	2	8025
Cum. total	8025	4922	3297	2115	1441	632	335	90	24	13	7	4	2	2	
	Once in given number of years														
Frequency	0 08	0.13	0 19	0 30	0 44	1 00	1 9	7 0	26 3	49	91	159	312	312	

State of Ohio

100 stations — 410 square miles per station

Year	Number of days with given daily precipitation — inches depth											Total days
	1 00 to 1 24	1 25 to 1 49	1 50 to 1 74	1 75 to 1.99	2 00 to 2 49	2 50 to 2 99	3 00 to 3 99	4 00 to 4 99	5 00 to 5 99	6 00 to 6 99	7 00 to 7.99	
1900	312	111	68	20	35	9	5	0	0	0	0	560
1901	235	139	89	54	46	17	10	3	0	0	0	593
1902	289	157	83	58	48	16	7	3	0	0	0	661
1903	357	153	75	38	44	18	6	2	1	1	0	695
1904	308	162	93	48	39	19	8	1	0	1	0	679
1905	354	173	124	53	69	22	11	3	1	0	0	810
1906	289	113	63	38	44	17	2	0	0	0	0	566
1907	409	188	94	63	57	16	8	4	0	0	0	839
1908	290	147	71	33	27	14	3	1	0	0	0	586
1909	351	177	131	58	53	9	14	5	1	0	0	799
1910	305	126	75	34	63	24	19	1	0	0	1	648
1911	291	156	92	53	59	23	22	3	0	0	0	699
1912	303	149	75	45	66	21	15	2	0	0	0	676
1913	337	159	97	77	109	46	34	11	2	2	1	875
1914	356	184	107	49	53	9	14	0	0	0	1	773
Total	4,786	2294	1337	721	812	280	178	39	5	4	3	10,459
Cum. total	10,459	5673	3379	2042	1321	509	229	51	12	7	3	
	Once in given number of years											
Frequency	0.17	0.32	0 54	0.89	1.39	3.57	8.0	35.7	151	263	610	

TABLE 4. — RECORDS OF EXCESSIVE DAILY PRECIPITATION — (*Continued*)

State of Kansas (eastern section)

42 stations — 643 square miles per station

Year	Number of days with given daily precipitation — inches depth													Total days
	1 00 to 1 24	1 25 to 1 49	1 50 to 1 74	1 75 to 1 99	2 00 to 2 49	2 50 to 2 99	3 00 to 3 99	4 00 to 4 99	5 00 to 5 99	6 00 to 6 99	7 00 to 7 99	8 00 to 8 99	9 00 to 9 99	
1900	109	59	54	32	46	17	16	3	4	0	0	.	..	340
1901	76	37	37	13	22	5	2	0	0	0	0		..	192
1902	128	81	56	40	58	23	10	2	0	0	0			398
1903	164	72	72	30	42	22	12	8	0	0	0		.	422
1904	129	71	53	36	61	23	25	4	2	1	0	.	.	405
1905	102	69	42	25	45	29	16	5	2	1	0			336
1906	97	57	42	18	25	11	12	8	3	1	1	.	.	275
1907	134	82	60	23	28	17	5	3	1	1	0	..	...	354
1908	173	103	78	37	65	35	28	5	4	1	0	...	.	529
1909	163	64	62	42	59	26	22	9	4	0	3	....	.	454
1910	129	67	55	29	39	9	8	2	0	0	0	....	...	338
1911	92	51	51	39	29	14	13	3	2	0	1	....	.	295
1912	122	90	55	50	51	15	15	2	1	2	0	. ..	.	403
1913	131	81	55	34	31	16	8	1	1	0	0	....	.	358
1914	149	78	50	45	39	21	21	2	3	1	1	....	....	410
Total .	1898	1062	822	493	640	283	213	57	27	8	6	. .	...	5509
Cum. total	5509	3611	2549	1727	1234	594	311	98	41	14	6		.	. . .
	Once in given number of years													
Frequency	0 09	0 13	0 19	0 28	0 40	0 83	1.6	5 0	12 0	35	82	. ..	....	

State of Kansas (western section)

26 stations — 1040 square miles per station

Year	Number of days with given daily precipitation — inches depth													Total days
	1 00 to 1 24	1 25 to 1 49	1 50 to 1 74	1 75 to 1 99	2 00 to 2.49	2.50 to 2 99	3 00 to 3 99	4 00 to 4.99	5.00 to 5.99	6.00 to 6 99	7 00 to 7.99	8 00 to 8 99	9 00 to 9 99	
1900	24	16	12	7	11	1	4	0	1	0	0	....	..	76
1901	28	11	14	5	5	3	0	1	0	0	1	....	...	68
1902	38	28	24	10	16	6	2	2	1	0	0	..	.	127
1903	37	14	10	7	7	0	4	3	1	0	0	.....	....	83
1904	45	21	17	8	7	2	1	0	0	0	0	....	....	101
1905	43	20	17	12	15	3	3	1	0	1	0	...	....	115
1906	54	26	22	9	12	2	0	0	1	0	0	...	....	126
1907	41	18	11	5	7	3	3	1	0	0	0	....	.....	89
1908	50	24	13	8	8	2	3	4	0	0	0	. ..	.....	112
1909	39	32	17	12	12	1	5	1	0	0	0	. ..	....	119
1910	17	11	7	1	6	3	1	1	0	0	0	....	....	47
1911	33	19	5	4	11	3	1	0	0	1	0	.....	....	77
1912	56	46	35	13	18	9	3	1	0	0	0	....	.....	181
1913	44	17	19	6	8	3	1	1	0	0	0	....	.....	99
1914	51	33	25	17	13	8	5	2	1	0	0	.....	.....	155
Total.....	600	336	248	124	156	49	36	18	5	2	1	.....	.....	1575
Cum. total	1575	975	639	391	267	111	62	26	8	3	1	.....	.....	......
	Once in given number of years													
Frequency	0 12	0.19	0 29	0 48	0.70	1.70	3.0	7.2	23.4	62 5	188	.....	.....	

TABLE 4. — RECORDS OF EXCESSIVE DAILY PRECIPITATION — (*Concluded*)

State of Kansas (middle section)

38 stations — 710 square miles per station

Year	Number of days with given daily precipitation — inches depth													Total days
	1.00 to 1.24	1.25 to 1.49	1.50 to 1.74	1.75 to 1.99	2.00 to 2.49	2.50 to 2.99	3.00 to 3.99	4.00 to 4.99	5.00 to 5.99	6.00 to 6.99	7.00 to 7.99	8.00 to 8.99	9.00 to 9.99	
1900	79	36	25	20	26	9	2	2	1	0	0	..	.	200
1901	62	35	12	6	6	6	2	0	0	0	0	..	..	129
1902	86	54	49	24	30	11	12	3	1	0	0	.	.	270
1903	89	58	39	23	45	18	13	2	1	0	0	..	..	288
1904	104	66	41	24	25	12	4	3	0	0	0		..	279
1905	92	59	41	22	39	7	13	5	0	0	1	.	..	279
1906	80	48	42	19	19	10	4	2	3	1	0		..	228
1907	90	43	35	26	21	9	7	1	0	0	0	..	..	232
1908	114	70	55	32	34	18	18	3	0	0	0	....	.	344
1909	103	54	39	26	42	23	8	4	0	0	0	.	..	299
1910	76	33	22	11	17	10	7	0	0	0	0	....	..	176
1911	98	57	33	30	16	6	8	2	0	0	0	...	...	250
1912	123	58	47	19	35	8	7	4	2	0	0	...	...	303
1913	89	50	32	23	15	4	2	1	0	0	0	...	..	216
1914	67	53	20	23	17	8	3	1	0	0	0	...	..	192
Total	1352	774	532	328	387	159	110	33	8	1	1	..	..	3685
Cum total	3685	2333	1559	1027	699	312	153	43	10	2	1	..	..	......
	Once in given number of years													
Frequency	0.11	0.17	0.26	0.39	0.57	1.3	2.6	9.3	40	200	400		..	

State of Alabama

65 stations — 800 square miles per station

Year	Number of days with given daily precipitation — inches depth													Total days
	1.00 to 1.24	1.25 to 1.49	1.50 to 1.74	1.75 to 1.99	2.00 to 2.49	2.50 to 2.99	3.00 to 3.99	4.00 to 4.99	5.00 to 5.99	6.00 to 6.99	7.00 to 7.99	8.00 to 8.99	9.00 to 9.99	
1901	343	202	188	113	178	62	58	24	7	4	4	1	0	1,184
1902	337	178	121	83	135	51	61	15	10	1	1	0	1	994
1903	340	186	158	86	141	42	48	13	6	2	1	0	1	1,024
1904	324	175	103	73	66	12	13	6	0	0	0	0	0	772
1905	340	185	150	96	134	53	40	13	7	1	1	0	0	1,020
1906	276	195	156	116	131	58	49	23	5	6	2	2	0	1,019
1907	368	221	159	98	159	52	23	12	0	2	1	0	0	1,095
1908	299	186	130	94	112	50	42	23	3	0	1	0	0	940
1909	358	245	200	120	161	55	59	22	3	0	0	0	0	1,223
1910	275	188	128	63	87	28	18	5	4	1	0	0	0	797
1911	383	206	145	78	149	48	40	10	1	1	0	1	0	1,062
1912	414	248	197	122	176	88	76	18	4	1	0	0	1	1,345
1913	315	190	143	95	142	63	48	13	4	2	0	1	0	1,016
1914	295	189	128	70	102	38	24	2	1	0	0	0	0	849
1915	306	192	138	124	154	68	62	28	7	2	1	0	0	1,082
Total.....	4,973	2,986	2244	1431	2027	768	661	227	62	23	12	5	3	15,422
Cum. total	15,422	10,449	7463	5219	3788	1761	993	332	105	43	20	8	3	.. ....
	Once in given number of years													
Frequency	0.04	0.06	0.08	0.12	0.16	0.35	0.6	1.8	5.8	14.1	30.5	76	203	

TABLE 5. — RECORDS OF EXCESSIVE MONTHLY PRECIPITATION

State of Minnesota, 1896–1915 incl.	Precipitation — inches per month															
	8 00 to 8 49	8 50 to 9 49	9 50 to 10 49	10 50 to 11 49	11 50 to 12 49	12 50 to 13 49	13 50 to 14 49	14 50 to 15 49	15 50 to 16 49							
Eastern section, 41 stations ...	87	84	45	23	12	11	5	1		.				.		..
1160 sq mi. per sta., Cumulative total	268	181	97	52	29	17	6	1			.				..	....
	Once in given number of years															
Frequency	1 32	1 95	3 6	6 8	12	21	59	500		.	.		.			.
Western section, 32 stations . .	23	19	16	7	4	2	1	2	1	.	.	.				....
1160 sq. mi. per sta., Cumulative total	75	52	33	17	10	6	4	3	1							.
	Once in given number of years															
Frequency ...	3 7	5 5	8 3	16 2	27 8	46 1	69	92	278			..	.	.	.	..

State of Ohio, 1894–1913 incl.	Precipitation — inches per month															
	7 00 to 7 99	8 00 to 8 99	9 00 to 9 99	10 00 to 10 99	11 00 to 11 99	12 00 to 12 99	13 00 to 13 99	14 00 to 14 99	15 00 to 15 99	16 00 to 16 99	17 00 to 17 99	18 00 to 18 99				
110 stations .	424	188	105	46	13	8	2	0	0	1	.		...	.		...
372 sq. mi. per sta., Cumulative total	787	363	175	70	24	11	3	1	1	1	.	...	. ..	..	...	...
	Once in given number of years															
Frequency	0 38	0 81	1.7	4.2	12 3	26 9	99	294	294	294	..	..	..	..	...	....

State of Kansas, 1894–1913 incl.	Precipitation — inches per month															
	7 00 to 7 99	8 00 to 8 99	9 00 to 9 99	10 00 to 10.99	11 00 to 11 99	12 00 to 12 99	13 00 to 13 99	14 00 to 14 99	15 00 to 15 99	16 00 to 16 99	17 00 to 17 99	18 00 to 18 99				
Eastern section, 44 stations	231	146	111	58	45	20	8	9	1	2	0	1	...	...	...	....
615 sq. mi. per sta., Cumulative total	632	401	255	144	86	41	21	13	4	3	1	1	..	.. .	....	....
	Once in given number of years															
Frequency.	1.13	1 8	2 7	5 0	8 3	17 4	34 1	55	178	238	715	715	....	.	. .	....
Middle section, 35 stations	111	68	35	23	12	6	5	2	0	0	2	....	.	...	...	....
600 sq. mi. per sta., Cumulative total	264	153	85	50	27	15	9	4	2	2	2	..	...	.. .	....	....
	Once in given number of years															
Frequency	2 2	3 8	6.9	11.7	21 6	39	65	146	290	290	290	. .	.	....	. .	....
Western section, 35 stations.........	44	10	10	11	3	3	..	...	...	....	...	....	....	....	....	....
940 sq. mi. per sta., Cumulative total	81	37	27	17	6	3	....	. .	....	....	....	....	....	....	....	....
	Once in given number of years															
Frequency.........	4.6	10.1	13.8	21.5	62.0	124	....	...	....	....	...	....	....	...	....	....

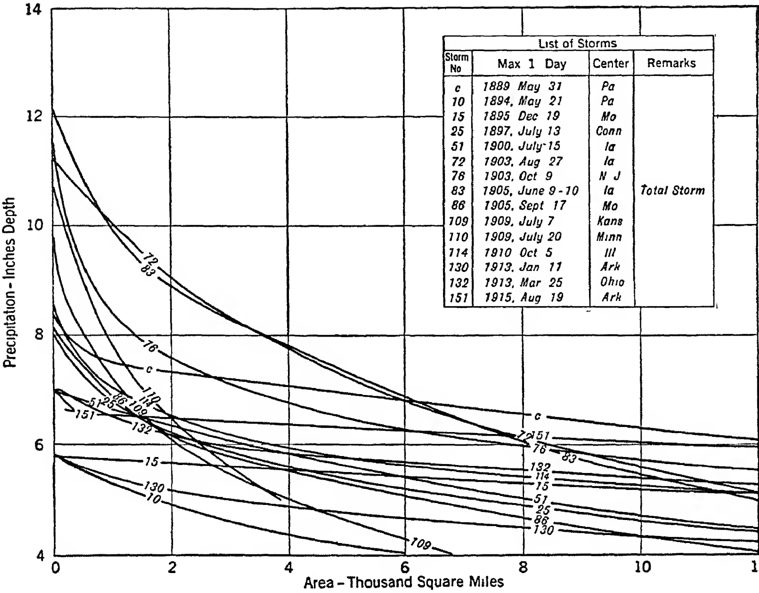
TABLE 5. — RECORDS OF EXCESSIVE MONTHLY PRECIPITATION — (*Concluded*)

State of Alabama, 1894–1913 incl.	Precipitation — inches per month															
	7.00 to 7.99	8.00 to 8.99	9.00 to 9.99	10.00 to 10.99	11.00 to 11.99	12.00 to 12.99	13.00 to 13.99	14.00 to 14.99	15.00 to 15.99	16.00 to 16.99	17.00 to 17.99	18.00 to 18.99	19.00 to 19.99	20.00 to 20.99	23.46	26.36
64 stations...... .	...	485	286	208	142	93	56	27	22	8	9	2	3	1	1	1
812 sq. mi. per sta., Cumulative total	....	1344	859	573	365	223	130	74	47	25	17	8	6	3	2	1
	Once in given number of years															
Frequency...... ..	. .	0.59	0.92	1.38	2.16	3.55	6.1	10.7	16.8	31.6	46	91	131	263	394	788

Typical Excessive Rainstorms. — A study has been made of typical storms of greatest recorded intensity in different parts of the United States. Maps of these storms are presented in Figs. 123 to 126 and the data on which the isohyetals are based are given in Tables 6 to 9. The relation between amount of precipitation and area covered by these severe storms is shown in Figs. 127 and 128.* The Beaulieu, Minnesota, and the Fort Madison, Iowa, storms were also studied in connection with the resulting floods on the Wild Rice River and Devil's Creek, respectively; hence the watersheds of these streams are also shown on the maps.

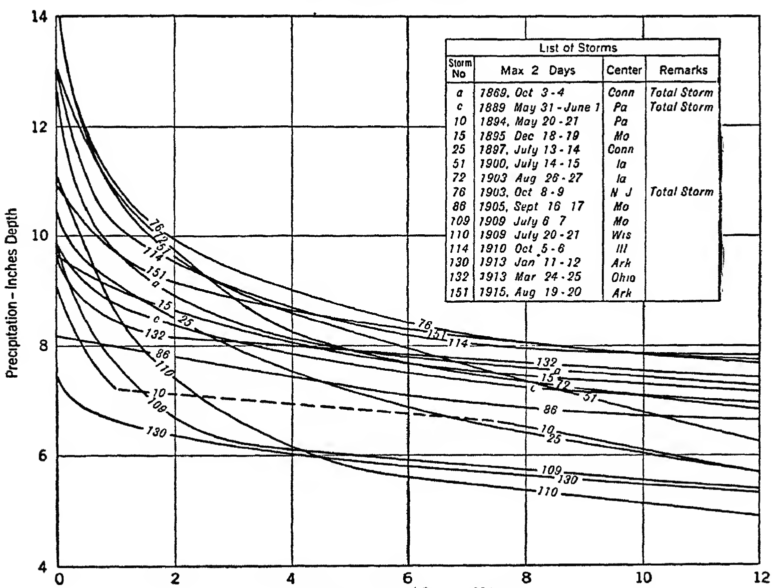
The storm paths are well indicated by the shape of the isohyetals. The Iowa storm came from the West, the Minnesota storm from the Northwest, and the Arkansas and Illinois storms from the Southwest. The first two storms lasted less than 24 hours. The Arkansas storm was a part of the destructive West Indian hurricane of August, 1915, and lasted $2\frac{1}{2}$ days. The Cairo, Illinois, storm extended over three days and was the greatest of all in extent and intensity. No serious floods resulted, however, because this storm centered over the lower reaches of large streams. The Ohio valley storm of March 23 to 27, 1913, while of much less severity, resulted in unprecedented stages on many streams because the heaviest precipitation occurred over the headwaters of the smaller northern tributaries.

* See pages 129 to 132, for similar curves taken from the exhaustive studies of the Miami Conservancy District, Dayton, Ohio.



Storm No	Max 1 Day	Center	Remarks
c	1889 May 31	Pa	
10	1894, May 21	Pa	
15	1895 Dec 19	Mo	
25	1897, July 13	Conn	
51	1900, July 15	Ia	
72	1903, Aug 27	Ia	
76	1903, Oct 9	N J	
83	1905, June 9-10	Ia	Total Storm
86	1905, Sept 17	Mo	
109	1909, July 7	Kans	
110	1909, July 20	Minn	
114	1910 Oct 5	Ill	
130	1913, Jan 11	Ark	
132	1913, Mar 25	Ohio	
151	1915, Aug 19	Ark	

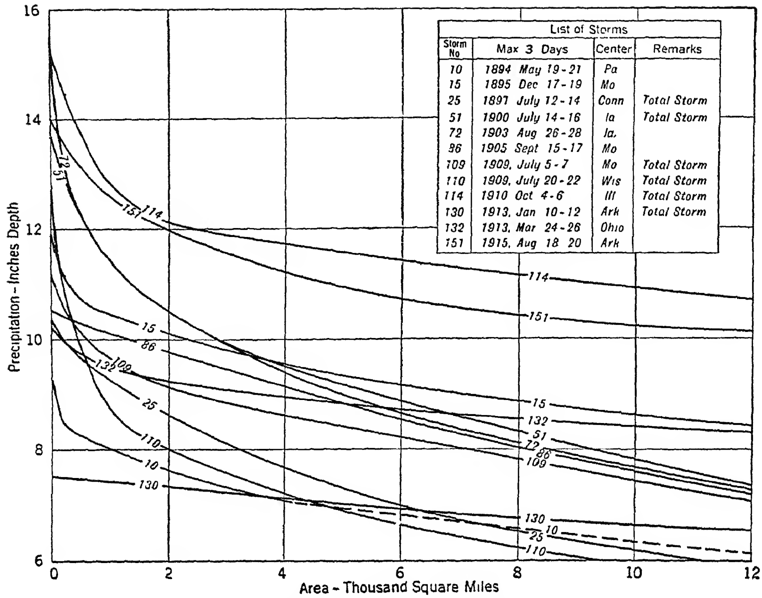
Relation of Depth of Precipitation to Area Covered by One-Day Storms (Northern States)



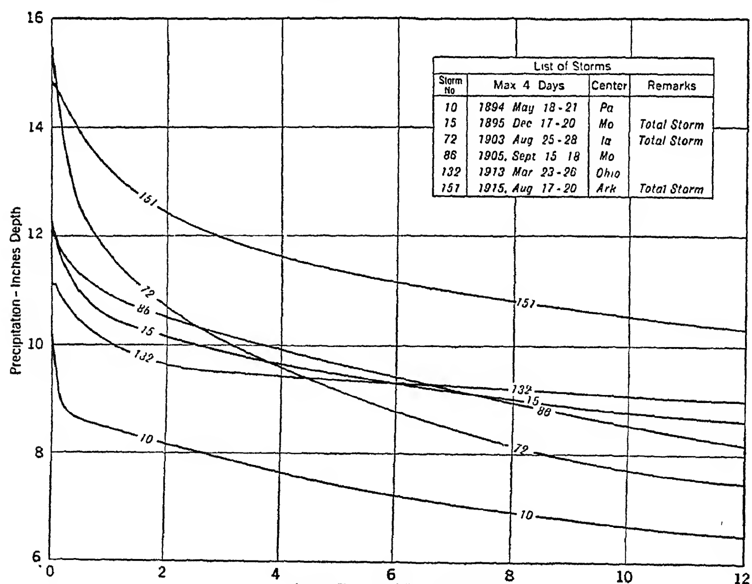
Storm No	Max 2 Days	Center	Remarks
a	1869, Oct 3-4	Conn	Total Storm
c	1889 May 31 - June 1	Pa	Total Storm
10	1894, May 20-21	Pa	
15	1895 Dec 18-19	Mo	
25	1897, July 13-14	Conn	
51	1900, July 14-15	Ia	
72	1903 Aug 26-27	Ia	
76	1903, Oct 8-9	N J	Total Storm
86	1905, Sept 16 17	Mo	
109	1909 July 6 7	Mo	
110	1909 July 20-21	Wis	
114	1910 Oct 5-6	Ill	
130	1913 Jan 11-12	Ark	
132	1913 Mar 24-25	Ohio	
151	1915, Aug 19-20	Ark	

Relation of Depth of Precipitation to Area Covered by Two-Day Storms (Northern States)

From Reports of Miami Conservancy District

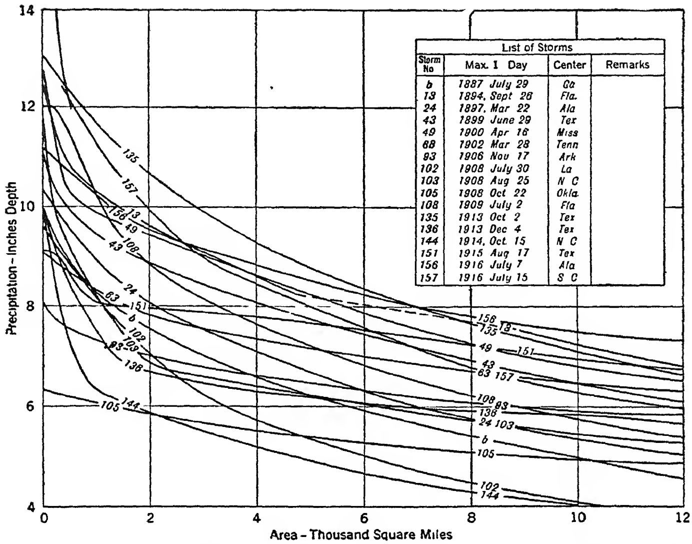


Relation of Depth of Precipitation to Area Covered by Three-Day Storms (Northern States)

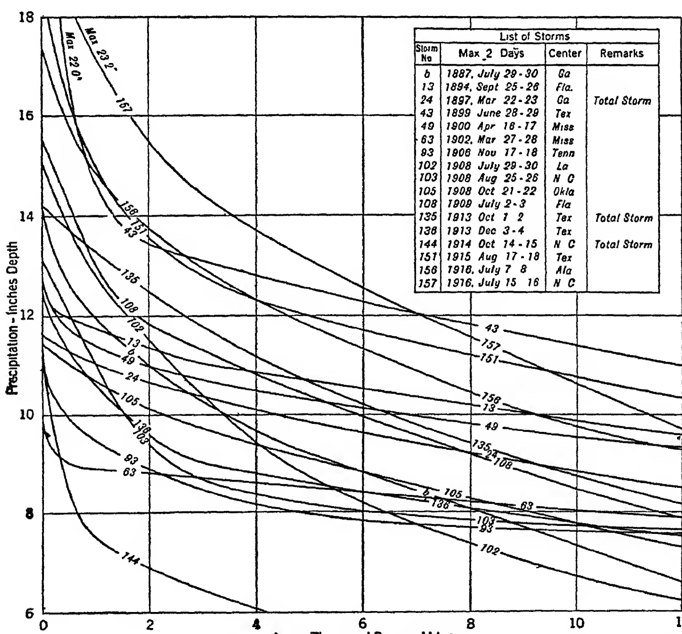


Relation of Depth of Precipitation to Area Covered by Four-Day Storms (Northern States)

From Reports of Miami Conservancy District

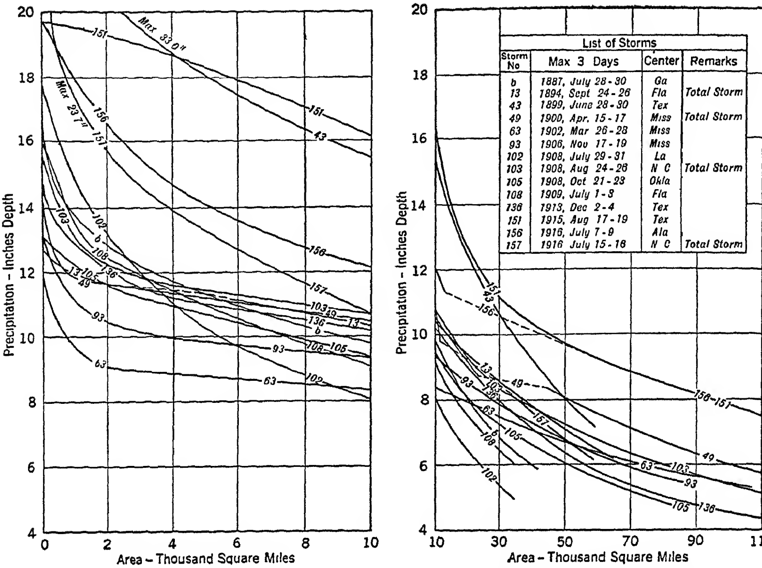


Relation of Depth of Precipitation to Area Covered by One-Day Storms (Southern States)



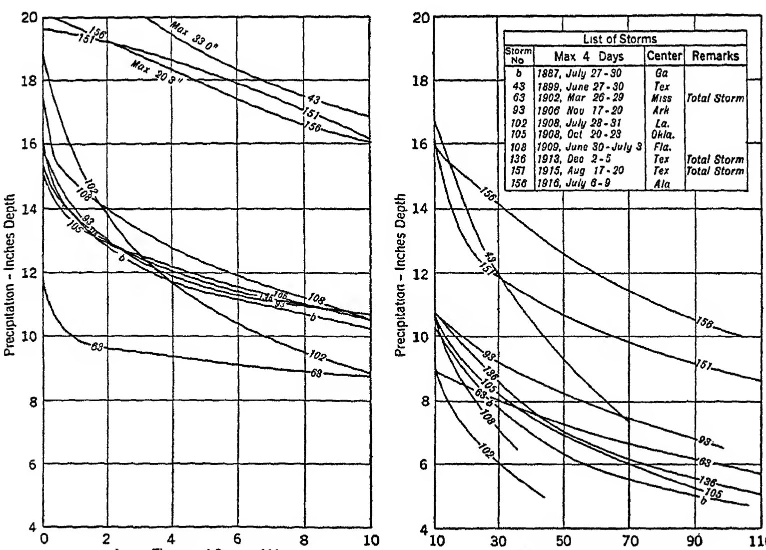
Relation of Depth of Precipitation to Area Covered by Two-Day Storms (Southern States)

From Reports of Miami Conservancy District



Storm No	Max 3 Days	Center	Remarks
b	1887, July 28-30	Ga	
13	1894, Sept 24-26	Fla	Total Storm
43	1899, June 28-30	Tex	
49	1900, Apr. 15-17	Miss	Total Storm
63	1902, Mar 26-28	Miss	
93	1906, Nov 17-19	Miss	
102	1908, July 29-31	La	
103	1908, Aug 24-26	N C	Total Storm
105	1908, Oct 21-23	Okla	
108	1909, July 1-3	Fla	
136	1913, Dec 2-4	Tex	
151	1915, Aug 17-19	Tex	
156	1916, July 7-9	Ala	
157	1916 July 15-16	N C	Total Storm

Relation of Depth of Precipitation to Area Covered by Three-Day Storms (Southern States)



Storm No	Max 4 Days	Center	Remarks
b	1887, July 27-30	Ga	
43	1899, June 27-30	Tex	
63	1902, Mar 26-29	Miss	Total Storm
93	1906 Nov 17-20	Ark	
102	1908, July 28-31	La.	
105	1908, Oct 20-23	Okla.	
108	1909, June 30-July 3	Fla.	
136	1913, Dec 2-5	Tex	Total Storm
151	1915, Aug 17-20	Tex	Total Storm
156	1916, July 6-9	Ala	

Relation of Depth of Precipitation to Area Covered by Four-Day Storms (Southern States)

From Reports of Miami Conservancy District

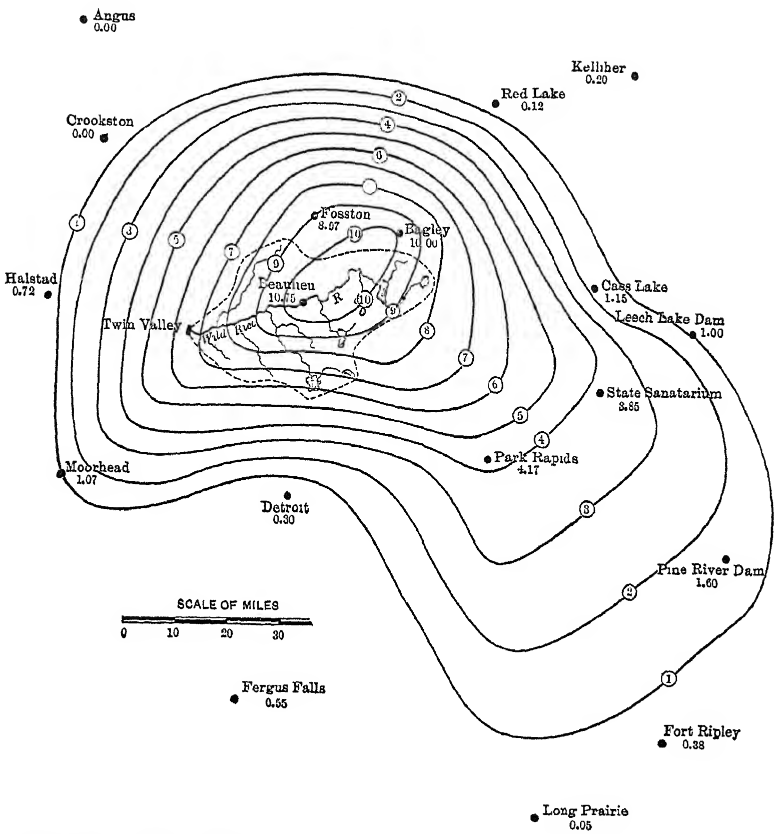


FIG. 123. — Map of Beaulieu, Minnesota, Storm, July 20, 1909. Less-than-one-day Storm.

See page 137 for tabulated precipitation.

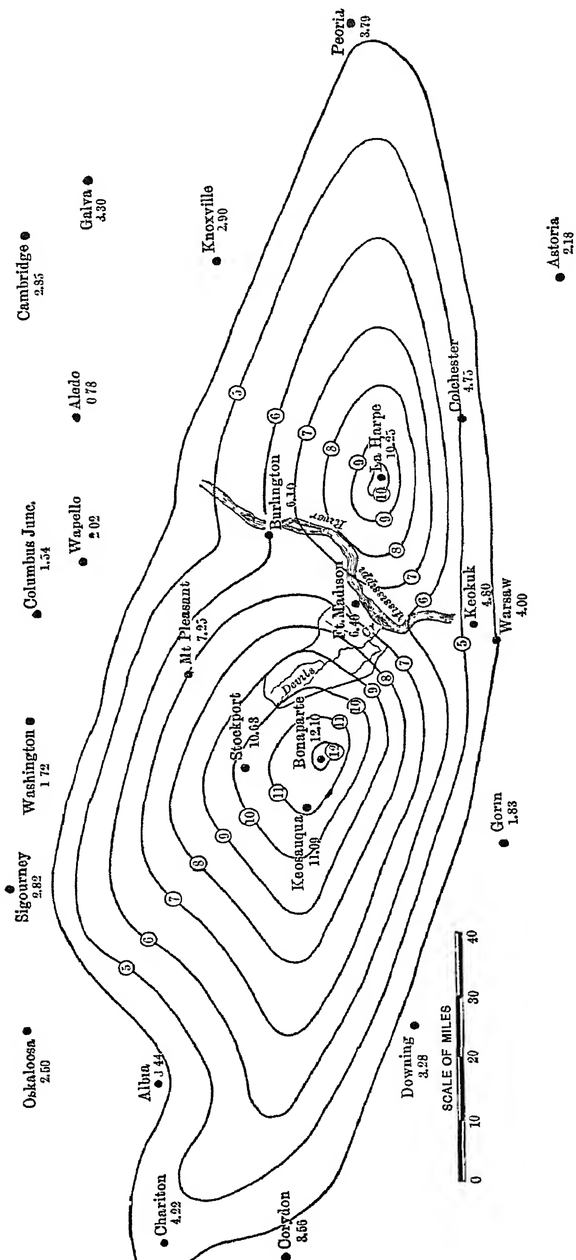


FIG. 124. — Map of Fort Madison, Iowa, Storm, June 9–10, 1905. Less-than-one-day Storm.

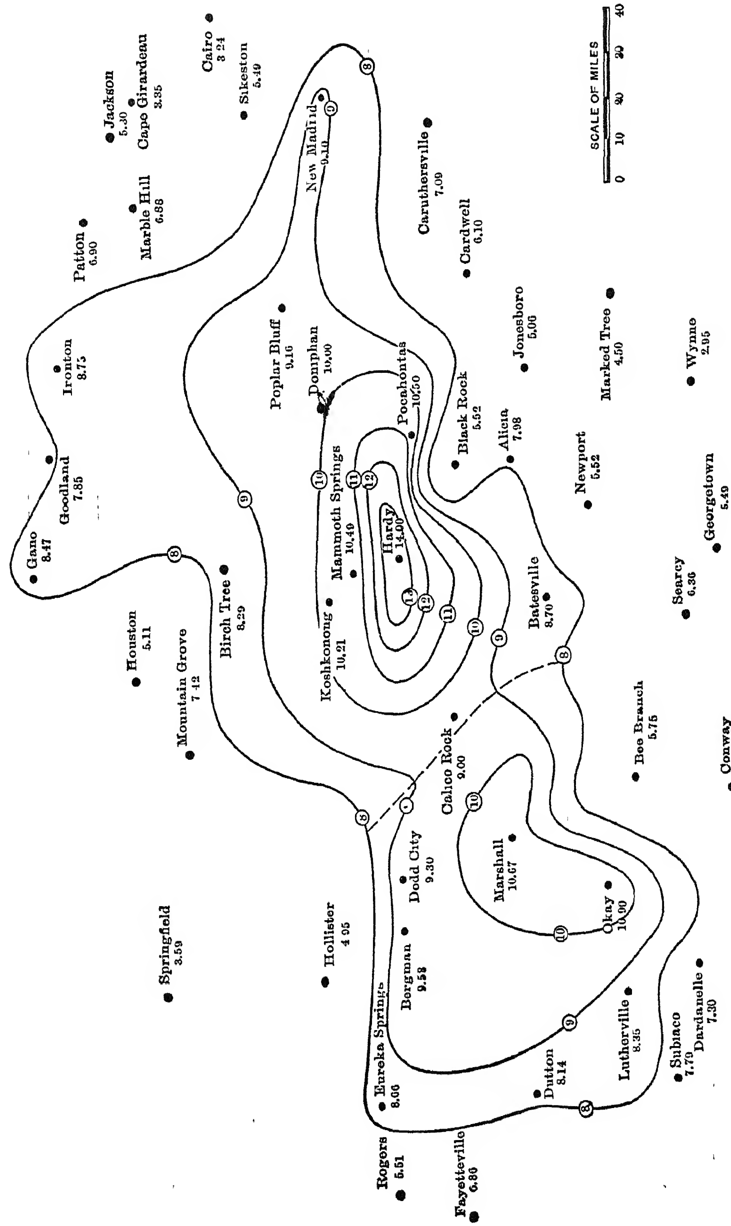


FIG. 125. — Map of Hardy, Arkansas, Storm, August 18, 19, 20, 1915. Two-and-a-half-day Storm.

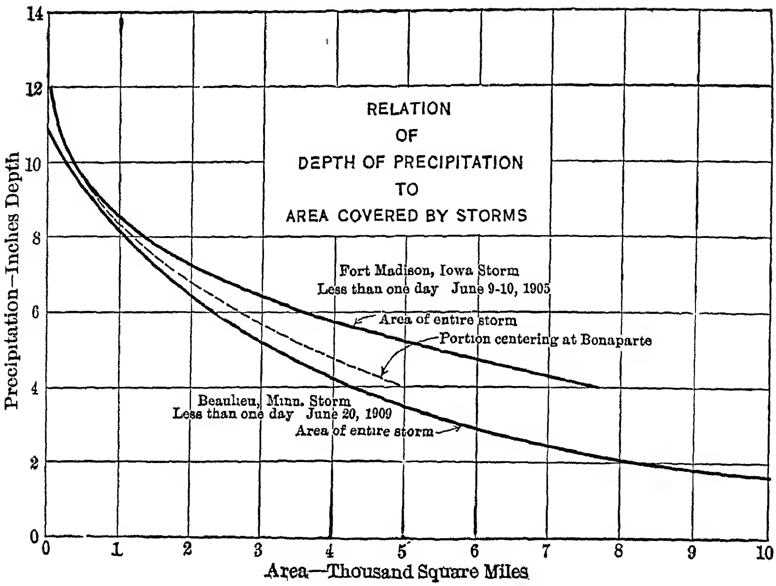


Fig. 127.

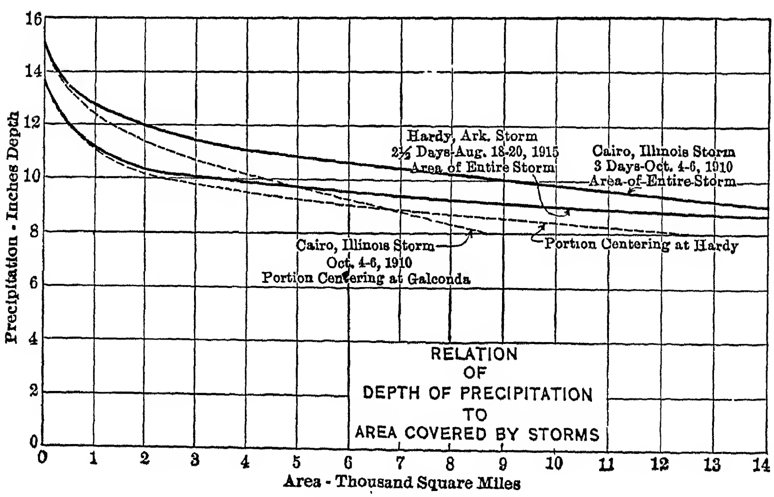


Fig. 128.

TABLE 6. — DATA FOR BEAULIEU, MINNESOTA, STORM
July 20, 1909
(Less than 24 hours)

Station		Precipitation — inches			
		19th	20th	21st	Plotted
Angus	Minn.	3 11	T	0 03	....
*Crookston	"	1 07	T	0.16	....
Red Lake	"	2 70	0.12	....	0.12
Kelliher	"	1.09	0 20	0 07	0.20
Fosston	"	†8.97	....	0 16	8.97
Bagley	"	1.20	10.00	0 08	10.00
*Halstad	"	0.12	1 29	0 72	0.72
Beaulieu	"	0.97	10.75	0 28	10.75
Cass Lake	"	1.10	1.15	0.38	1.15
Leech Lake, dam	"	1.40	1 00	0 47	1.00
State Sanatarium	"	2.10	3.85	1 25	3.85
*Park Rapids	"	0.16	4 17	1 55	4.17
Detroit	"	....	0 30	4.50	0.30
Moorhead	"	....	1.07	0 20	1.07
Pine River dam	"	T	1 60	1 20	1.60
Fergus Falls	"	....	0 55	2.50	0.55
*Fort Ripley	"	....	0.38	1 38	0.38
Long Prairie	"	0	0 05	2.00	0.05

* Precipitation for 24 hours ending on morning when measured.
† Rain fell during night of 19th to 20th, 5.30 P.M. to 10.30 P.M.

Precipitation	Extent of storm area in square miles
Over 1 inch	10,590
" 2 "	7,970
" 3 "	5,750
" 4 "	4,180
" 5 "	3,230
" 6 "	2,370
" 7 "	1,660
" 8 "	1,040
" 9 "	566
" 10 "	224

Area of watershed of Wild Rice River at Twin Valley 805 square miles. Average precipitation over watershed 8.82 inches.

See page 133 for Map of storm.

TABLE 7. — DATA FOR FORT MADISON, IOWA, STORM

June 9–10, 1905

(Less-than-one-day storm)

Station		Precipitation — inches		
		9th	10th	Plotted
Chariton	Iowa	4 22	....	4.22
Corydon	"	T	3.56	3.56
Oskaloosa	"	1 30	1.20	2.50
Albia	"	....	3 44	3 44
Downing	"	T	3 28	3.28
Sigourney	"	0 09	2 73	2 82
Washington	"	....	1 72	1.72
Mt. Pleasant	"	0 05	7 20	7 25
Stockport	"	....	10 63	10 63
Keosauqua	"	....	11.09	11.09
Bonaparte	"	....	12.10	12 10
Gorin	"	....	1.83	1.83
Columbus, Jct.	"	0 10	1 44	1 54
Wapello	"	0 02	2 00	2.02
Burlington	"	0 06	6 04	6 10
Ft. Madison	"	....	6 40	6.40
La Harpe	"	....	10 25	10 25
Keokuk	"	2 18	2 62	4 80
Warsaw	"	....	4 00	4 00
Colchester	Ill.	0 05	4 70	4 75
Astoria	"	0 04	2 14	2 18
Peoria	"	1 25	2 54	3 79
Knoxville	"	0 15	2.75	2 90
Galva	"	0 32	2 98	3 30
Cambridge	"	....	2 85	2 85
Aledo	"	....	0 78	0.78

Precipitation	Extent of storm area in square miles		
	Center at Bonaparte	Center at La Harpe	Entire storm
Over 4 inches	4890	2780	7670
" 5 "	3575	1865	5440
" 6 "	2645	1130	3775
" 7 "	1837	588	2425
" 8 "	1172	263	1435
" 9 "	697	70	767
" 10 "	342	10	352
" 11 "	123	....	123
" 12 "	13	....	13

Area of watershed of Devil's Creek at railroad bridge 143.5 square miles. Average precipitation over watershed 8.72 inches.

TABLE 8. — DATA FOR HARDY, ARKANSAS, STORM
August 18–20, 1915
(Two-and-a-half-day storm)

Station		Precipitation — inches					
		17th	18th	19th	20th	21st	Plotted
Springfield	Mo.	1.97	0 17	3 04	0 38	......	3 59
Hollister	"	. . .	1 55	2 00	1.40	. ...	4 95
*Mountain Grove	"	. ...	2 04	0 68	4.70	0.26	7.42
Houston	"	T	1 10	1.71	2 30	.....	5.11
Gano	"	. ...	2 16	1.14	5 17	......	8 47
Birch tree	"	0 05	2 93	3.08	2 28	... .	8.29
Goodland	"	.. ...	.....	2 85	5 00	.. .	7 85
*Ironton	"	.....	0 52	0 65	6 70	1.40	8 75
Patton	"	1 45	1 45	0.95	4.50	....	6 90
Marble Hill	"	. . .	1 25	1 02	4 61	.... .	6.88
Jackson	"	0.02	0.85	4 10	0 35	. ..	5.30
Cape Girardeau	"	.. ..	....	. . . .	3 35	0 35	3 35
Sikeston	"	0 22	1.26	1 08	3.15	...	5.49
Poplar Bluff	"	T	3 00	0 86	5 30	0.13	9.16
Doniphan	"	T	4 00	2 40	3 60	......	10 00
*New Madrid	"	.....	2 60	2 40	4.10	.....	9.10
Caruthersville	"	T	1 65	3 70	1 74	.....	7.09
Cardwell	"	T	0 96	2 82	2 32	..	6.10
Koshkonong	"	.....	2.87	*	*	7 34	10 21
Rogers	Ark.	....	0.81	4 09	0.61	......	5 51
Fayetteville	"	.....	1 49	4 96	0.41	.....	6 86
Eureka Springs	"	.....	1 20	5.43	2.03	......	8 66
Dutton	"	T	1.73	6 13	0.28	......	8.14
Lutherville	"	1.68	6.42	0 25	......	......	8.35
Subiaco	"	......	1.87	5 92	. ....	......	7.79
*Dardanelle	"	0 50	......	2 00	5 30	......	7.30
Okay	"	0 05	*	*	10.90	......	10.00
Marshall	"	0 51	3 25	6.33	1.09	......	10 67
Bergman	"	......	2.45	5.70	1.43	....	9.58
Dodd City	"	......	......	*	*	9 30	9 30
*Calico Rock	"	......	1.12	1.78	6.10	0.10	9 00
Bee Branch	"	.....	0.25	4 90	0.60	......	5.75
Conway	"	......	......	3.10	0.11	.....	3.21
*Georgetown	"	......	......	2.19	3.30	0.04	5.49
Seavey	"	......	0.16	5.33	0.87	......	6.36
*Newport	"	......	0.45	2.05	3.02	0.15	5.52
*Batesville	"	......	1 00	2.26	5.44	T	8.70
Alicia	"	1.35	4.08	2.50	1.40	......	7.98
*Black Rock	"	......	1.95	1.46	2.11	0.05	5.52
Hardy	"	0.80	5.45	6.70	1 85	......	14.00
Mammoth Springs	"	......	3.50	3.05	3.94	......	10.49
Pocahontas	"	0.08	3 50	3.80	3.20	......	10.50
Jonesboro	"	.....	0.80	2.73	1.53	......	5.06
*Marked Tree	"	......	0 01	1.80	2.69	0.10	4.50
Wynne	"	......	......	0.89	2.06	......	2.95
†Cairo	Ill.	0.13	0.66	1.34	1.24	......	3.24

* Precipitation measured in morning. Amount then recorded is for preceding 24 hours.
† Regular Weather Bureau Station precipitation is for 24 hours period, midnight to midnight.

TABLE 8.—DATA FOR HARDY, ARKANSAS, STORM—(*Concluded*)
August 18–20, 1915
(Two-and-a-half-day storm)

Precipitation	Extent of storm area in square miles		
	Center at Hardy	Center at Marshall	Entire storm
Over 8 inches	12,600	6,400	19,000
" 9 "	6,100	4,000	10,100
" 10 "	2,380	1,010	3,390
" 11 "	970	....	970
" 12 "	460	....	460
" 13 "	170	....	170

TABLE 9.—DATA FOR CAIRO, ILLINOIS, STORM
October 4, 5, 6, 1910
(Three-day storm)

Station	Precipitation — inches					
	3d	4th	5th	6th	7th	Plotted
Perryville, Mo.	. .	2.80	2.00	0.95	....	5.75
Jackson, "	3 52	....	3.16	0.90	. ..	7.58
Marble Hill, "	0.43	2.40	3.20	1.05	.....	6.65
Doniphan, "	T	2 01	4.33	0.93	.....	7.27
Sikeston, "	0.11	5.50	4.00	1.90	.	11.40
*New Madrid, "	..	5.20	1.86	6.24	0 11	13.30
Caruthersville, "	0 11	4 15	3.10	3 00	. . .	10 25
Koshkonong, "	0 25	1.35	1.43	0 60	. ..	3 38
Sparta, Ill.	0 76	2.18	1.15	0.51	......	3.84
Carbondale, "	. . .	4.42	4 25	1.07	.. .	9.74
Equality, "	.	5.24	5.47	2.04	...	12.75
*New Burnside, "	T	0.11	4.86	5.86	1.37	12.09
Cobden, "	T	5 10	4.60	1.10	......	10.80
Golconda, "	. .	4.95	7.99	2.24	. ..	15.18
Cairo, "	1.29	4.47	4.77	0.42	......	9.66
*Chester, "	0.28	2.96	0.98	1.13	.... .	5.07
Edwardsville, "	0.20	0.42	3.05	0.50	... .	3 97
*E. St. Louis, "	0	0.62	0.03	2.33	.....	2.98
Mascoutah, "	0.81	. ...	2.87	0.45	......	3.32
Carlyle, "	......	1.40	2.10	0.60	... .	4.10
Mt. Vernon, "	... ..	4.18	0.45	1.64	0.02	6.27
St. Peter, "	T	1.55	1.75	0.35	......	3.65
Flora, "	0.19	3.40	2.50	0.85	......	6.75
Olney, "	0.42	2.69	2.40	0.52	......	5.61
Sumner, "	T	3.41	3.11	0.87	. ....	7.33
*Mt. Carmel, "	...	3.10	2.06	2.76	T	7.92
Albion, "	. .	3.42	2.22	1.23	....	6.87
Fairfield, "	0.17	3.85	1.79	1 31	...	6.95
Corning, Ark.	1.23	3.97	2.00	1.40	. ..	7.37

* Precipitation for the 24 hours ending on the morning when it is measured.

TABLE 9. — DATA FOR CAIRO, ILLINOIS, STORM — (*Continued*)
October 4, 5, 6, 1910
(Three-day storm)

Station	Precipitation — inches					
	3d	4th	5th	6th	7th	Plotted
Pocahontas .... Ark.	0.13	2.23	2.14	1.35		5.72
*Black Rock .... "	1.32	0.72	2.59	....	.	3 31
Alicia............. "	0 20	2 25	4.95	....	...	7 20
Jonesboro........... "	0.70	2 80	2.70	1.00	. .	6 50
*Batesville......... "	1.34	1.38	4.32	....	...	5 70
*Newport........... "	...	3.00	0.20	6.00	.	9.20
*Marked Tree.......... "	....	2.16	4.38	7.45	..	13.99
Earl............... "	...	1 72	2.41	0.84	...	4.97
Mammoth Spring...... "		0.68	1.88	0.90	.	3.46
Hardy............. "	0.06	1.14	3.35	0.65	..	5.14
*Calico Rock......... "	..	0.68	2.00	1.00	...	3.68
Bee Branch........... "	.	0.50	8.50	2.50	....	11.50
Conway............ "	0.27	0.83	0.65	0.86	......	2 34
Dodd City............. "	T	†	2.79	.....	......	2.79
Mossville............. "	....	1.60	0.60	.....	....	2 20
Lutherville.......... "	0.04	1.03	3.52	0.52	......	5.07
*Dardanelle........... "	.....	0.12	1.32	3.44	.....	4.88
*Wynne............... "	.	2.02	1.89	4.60	0.01	8.51
Brinkley........... "	..	0.78	0.52	2.61	....	3.91
*Owensboro............Ky.	.....	0.20	2.62	5.31	0.33	8.26
Calhoun.............. "	T	1.37	3.88	4.82	....	10.07
*Beaver Dam.......... "	....	...	.....	4.30	0.50	4 80
*Earlington.......... "	0.07	...	1.06	5.60	0.15	6.81
*Hopkinsville.......... "	....	1.00	1.20	3.85	....	6.05
Cadiz................ "	0.17	0.97	7.08	0.74	.....	8.79
Marion............... "	T	1.75	4.92	2.78	.....	9.45
*Paducah........... "	...	1.90	2.00	5.00	0.12	9.02
Blandville............ "	0.30	4.23	4.29	1.78	......	10.30
Lynville............. "	T	1.32	......	5.50	....	6.82
Kenton..............Tenn.	0.47	1.36	1.50	4.90	......	7.76
*Dyersburg............ "	.....	0.67	1.00	6.20	.....	7 87
*Covington.......... "	.....	0.75	0.08	8.35	0.10	9.18
Memphis............. "	0.55	0.01	3.65	0.52	.....	4.18
Jackson.............. "	....	0.50	3.10	0.05	.....	3.65
*Arlington............. "	.....	0.78	T	3.20	T	3 98
*Brownsville........... "	.....	0.25	0.19	6.00	0.98	7.42
*Milan................ "	.....	0.01	0.41	5.25	0.10	5.67
Trenton............. "	T	0.30	2.00	4.00	.....	6.30
Union City........... "	....	1.87	2.25	2.27	0.12	6.39
Dover.............. "	...	0.60	1.60	4.07	.....	6.27
Springville............ "	.....	0.22	1.19	4.54	......	5.95
Mt. Vernon............Ind.	......	2.36	3.32	4.36	0.10	10.04
Evansville............ "	0.17	3.66	6.50	0.55	.....	10.71
Rome................ "	.....	0.95	2.60	4.48	0.01	8.03
Princeton............ "	......	2.83	3.50	......	......	6.30
Huntingburg.......... "	......	3.70	4.45	2.15	......	10.30
Paoli................ "	.....	1.95	4.37	1.80	......	8.12

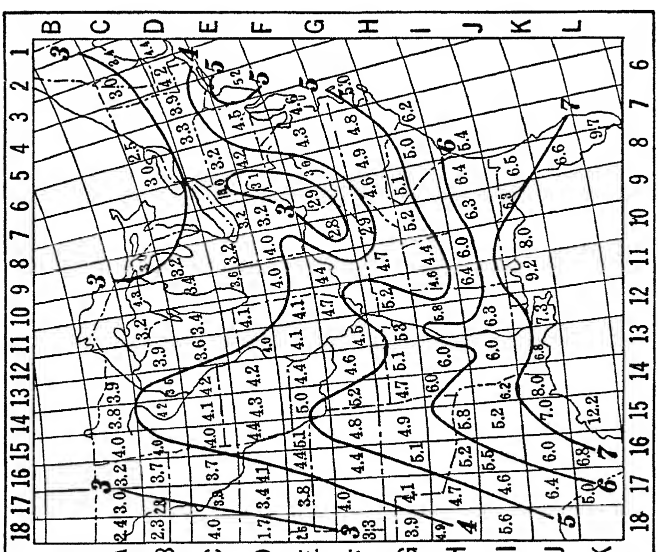
* Precipitation for the 24 hours ending on the morning when it is measured.
† Precipitation included in that of the next measurement.

TABLE 9. — DATA FOR CAIRO, ILLINOIS, STORM — (*Continued*)
October 4, 5, 6, 1910
(Three-day storm)

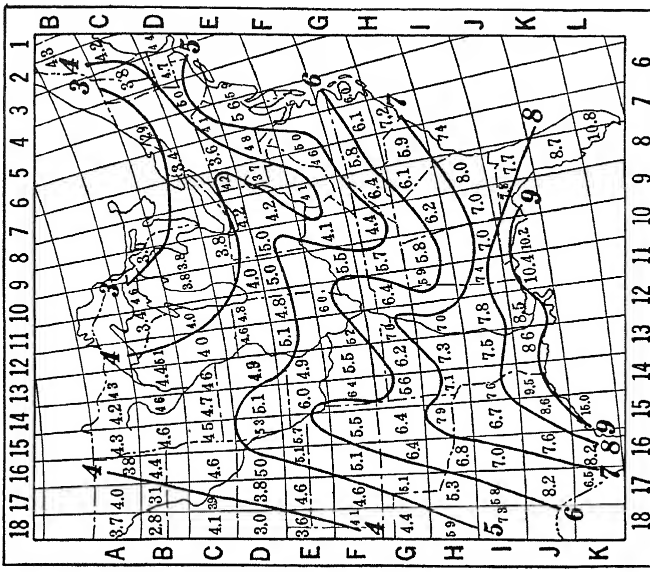
Station		Precipitation — inches					
		3d	4th	5th	6th	7th	Plotted
Vincennes	Ind.		2 80	2 00	3 20	T	8 00
Farmersburg	"	0 05	2 10	1 99	0 57	.	4.66
Worthington	"		1.71	3.90	0.75		6 36
Marengo	"		0.41	4.00	0.89		5.30
Salem	"		1.10	4 80	2 57		8 47
Jeffersonville	"	.	0.75	2 25	3.37	.	6.37
Scottsburg	"	.	0 36	4 96	2.90		8 22
Seymour	"		0 92	3.70	1.88		6.50
Bloomington	"		0 70	4.00	4 02	0 08	8 72
Columbus	"		0 14	4.12	4.00	0.24	8 26
Shelbyville	"	.	1.77	3.05	1.53		6 35
Greensburg	"		0 87	4.02	1.82	.	6.11
Butlerville	"		0 30	4.88	3 38	.	8 56
Madison	"		0 54	2 43	4 86	.	7.83
Moore's Hill	"	.	0.09	4.03	4 30	.	8.42
Mauzy	"		1 27	3.99	1.65	.	6 91
Connersville	"		0.88	4.29	1 85	. .	7.02
Cincinnati	Ohio	.	0 26	2 33	2 82	. . . .	5 41
Jacksonburg	"	.	0 11	....	7.50		7.61
Dayton	"	.	0 06	3 82	2 78	.	6.66
Waynesville	"			3 30	4 38		7.68

TABLE 9. — DATA FOR CAIRO, ILLINOIS, STORM — (*Concluded*)
October 4, 5, 6, 1910
(Three-day storm)

Precipitation	Extent of storm area in square miles					
	Center at Bee Branch, Ark.	Center at Marked Tree, Ark	Center at New Madrid, Mo.	Center at Golconda, Ill.	Center at Huntingburg, Ind.	Entire storm
Over 7 inches	3190	5860	7440	10,980	14,330	41,800
" 8 "	1850	4110	5400	8720	7780	27,860
" 9 "	972	2560	3820	6490	2210	16,052
" 10 "	356	1500	2285	4490	805	9436
" 11 "	44	780	1070	2530	....	4424
" 12 "	....	375	360	1365	....	2100
" 13 "	....	92	28	655	....	775
" 14 "	....	....	....	217	....	217
" 15 "	....	....	....	18	....	18

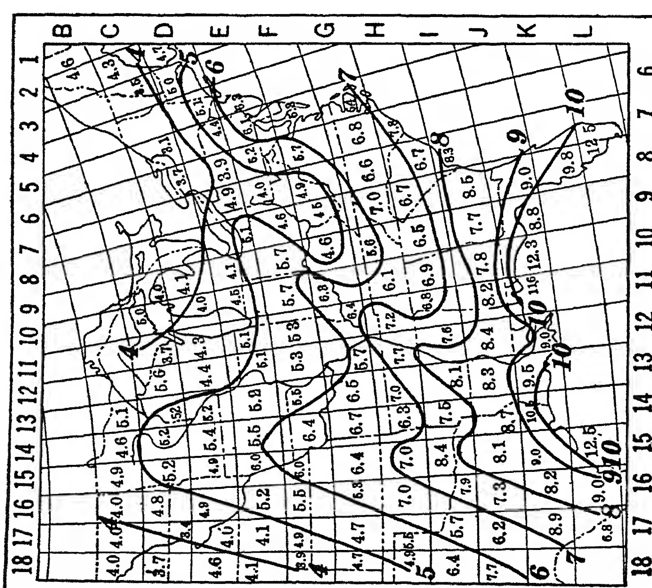


Isopluvial Chart for 15-Year Period and 1-Day Rainfall

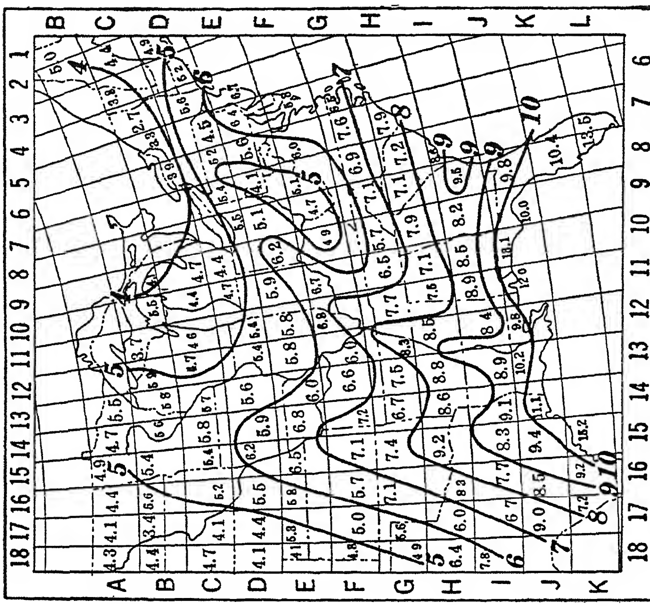


Isopluvial Chart for 15-Year Period and 2-Day Rainfall

From Reports of Miami Conservancy District

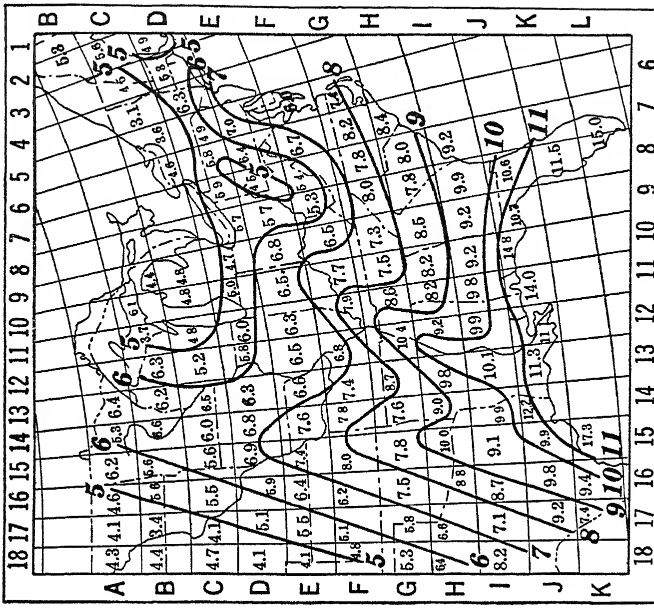


Isopluvial Chart for 15-Year Period and 3-Day Rainfall

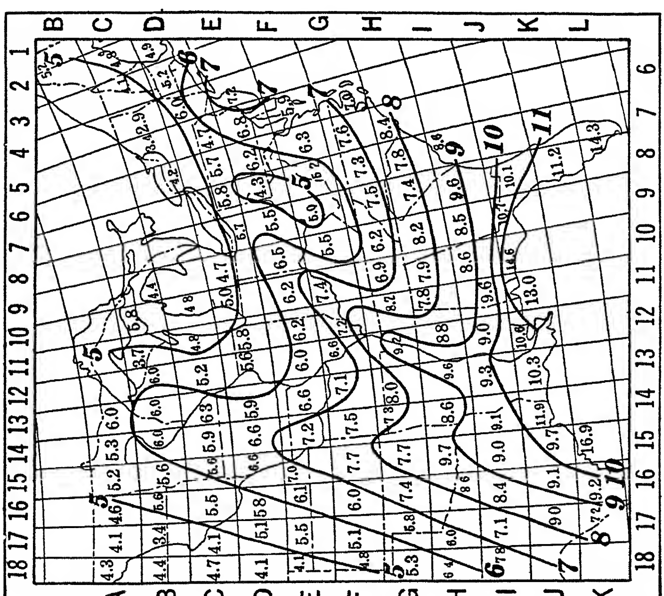


Isopluvial Chart for 15-Year Period and 4-Day Rainfall

From Reports of Miami Conservancy District

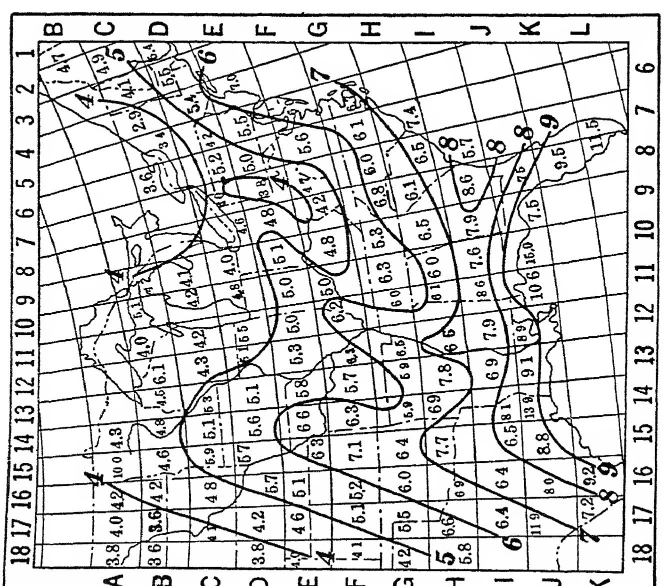


Isopluvial Chart for 15-Year Period and 6-Day Rainfall

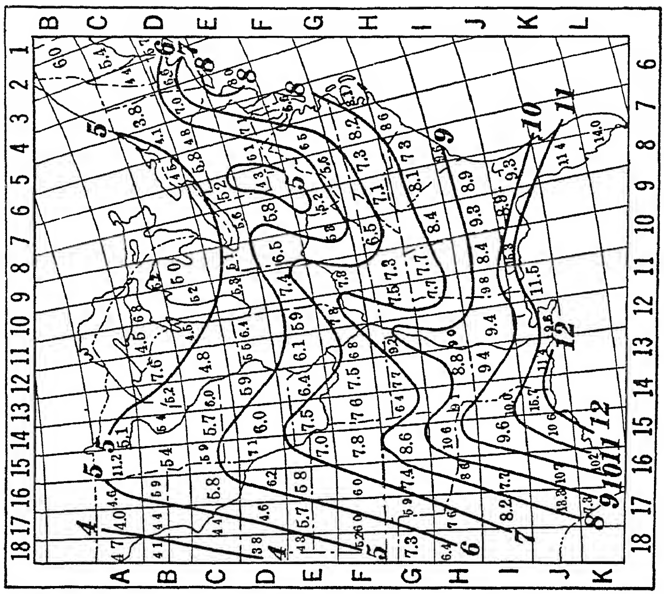


Isopluvial Chart for 15-Year Period and 5-Day Rainfall

From Reports of Miami Conservancy District

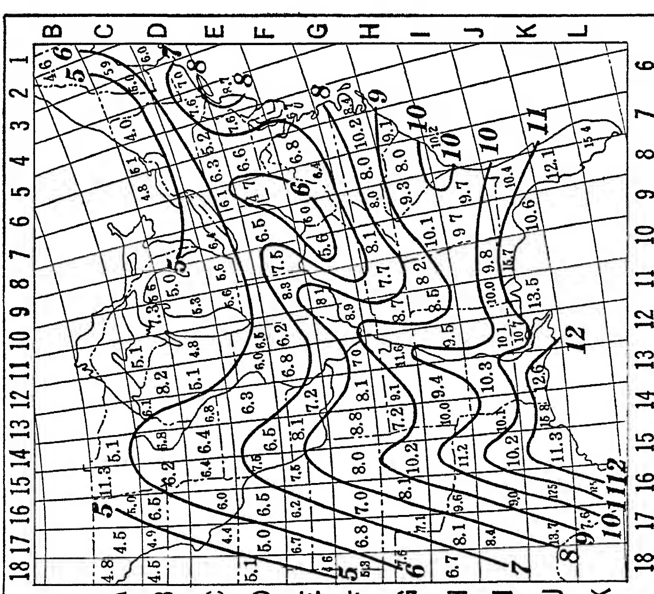


Isopluvial Chart for 50-Year Period and 1-Day Rainfall

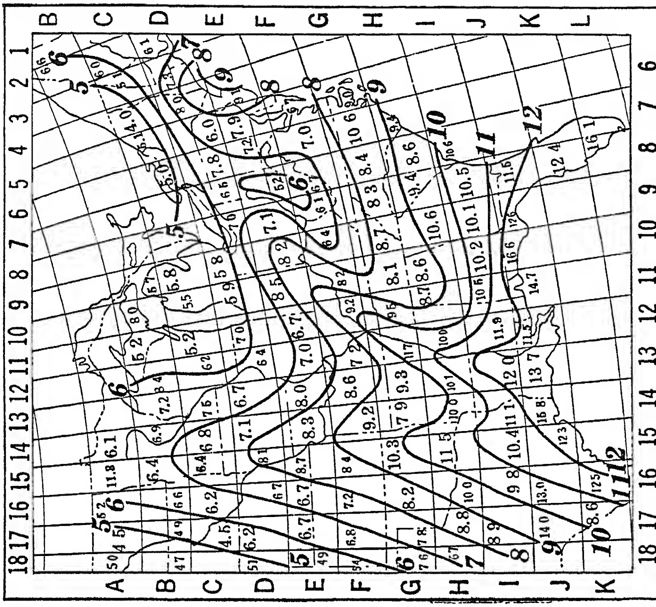


Isopluvial Chart for 50-Year Period and 2-Day Rainfall

From Reports of Miami Conservancy District

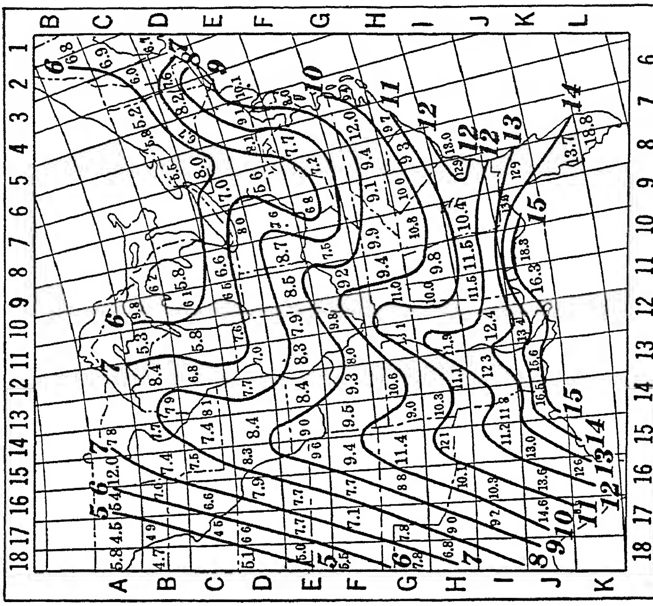


Isopluvial Chart for 50-Year Period and 3-Day Rainfall

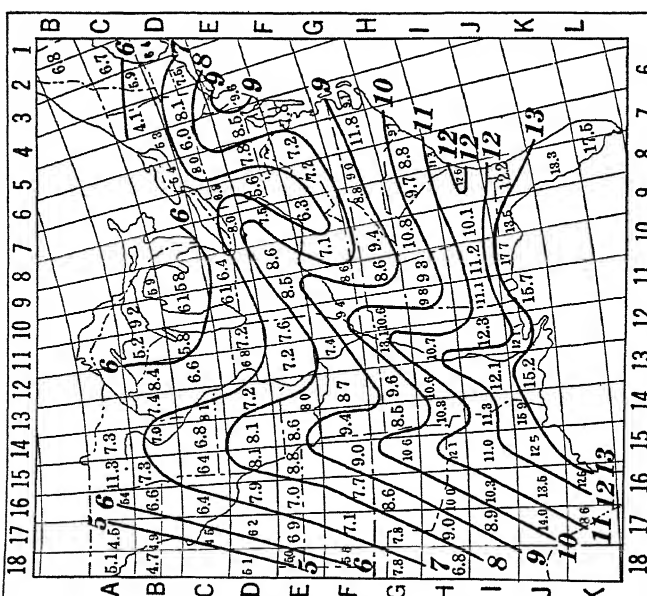


Isopluvial Chart for 50-Year Period and 4-Day Rainfall

From Reports of Miami Conservancy District

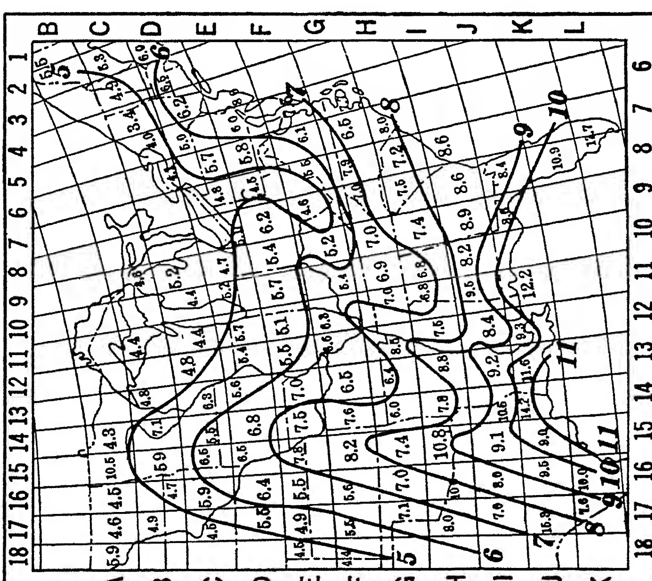


Isopluvial Chart for 50-Year Period and 6-Day Rainfall

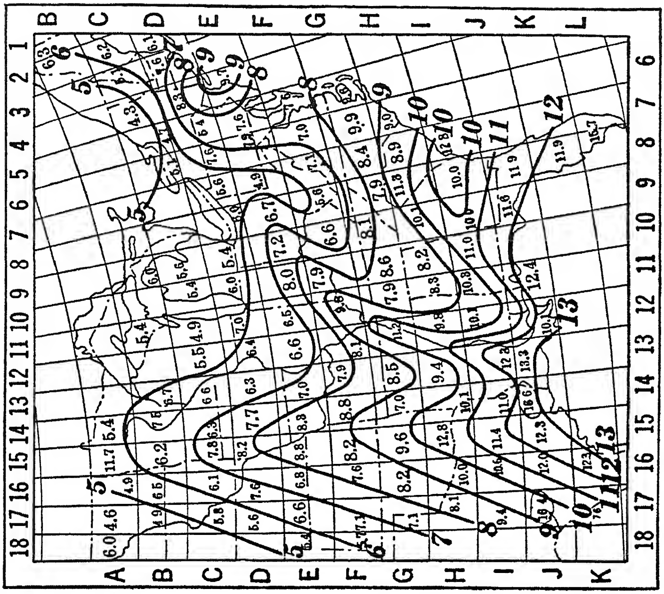


Isopluvial Chart for 50-Year Period and 5-Day Rainfall

From Reports of Miami Conservancy District

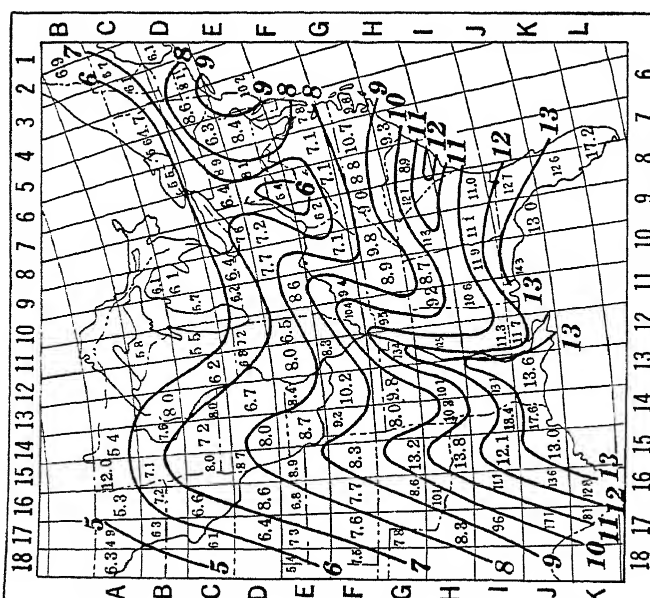


Isopluvial Chart for 100-Year Period and 1-Day Rainfall

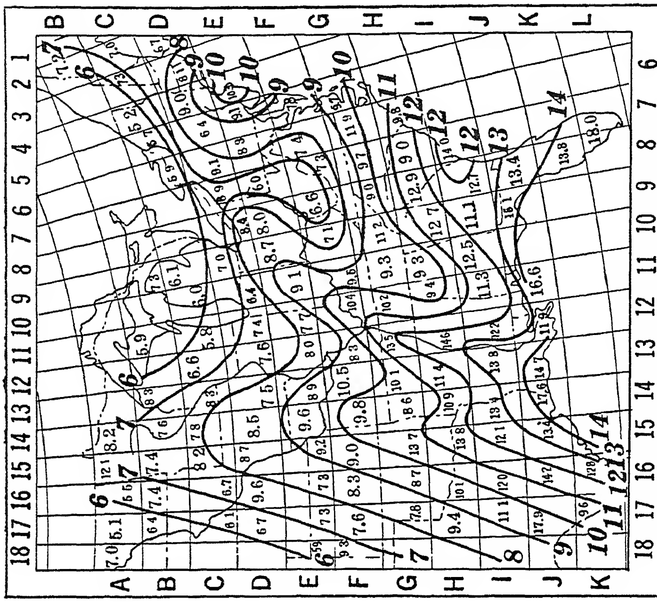


Isopluvial Chart for 100-Year Period and 2-Day Rainfall

From Reports of Miami Conservancy District

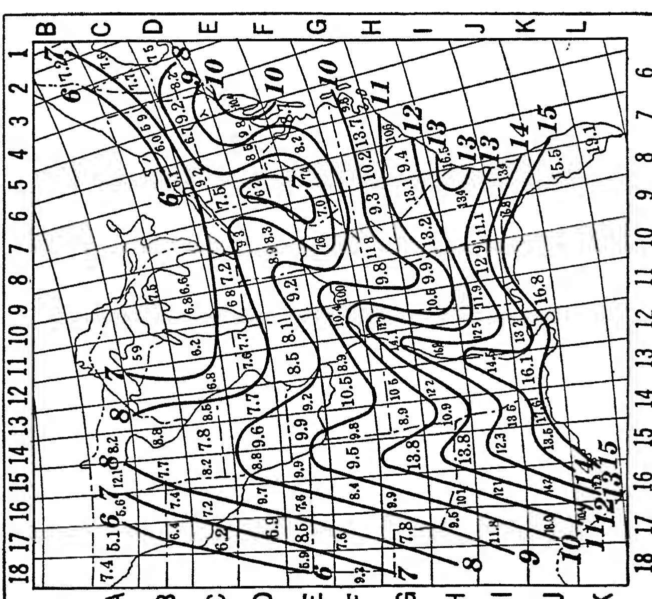


Isopluvial Chart for 100-Year Period and 3-Day Rainfall

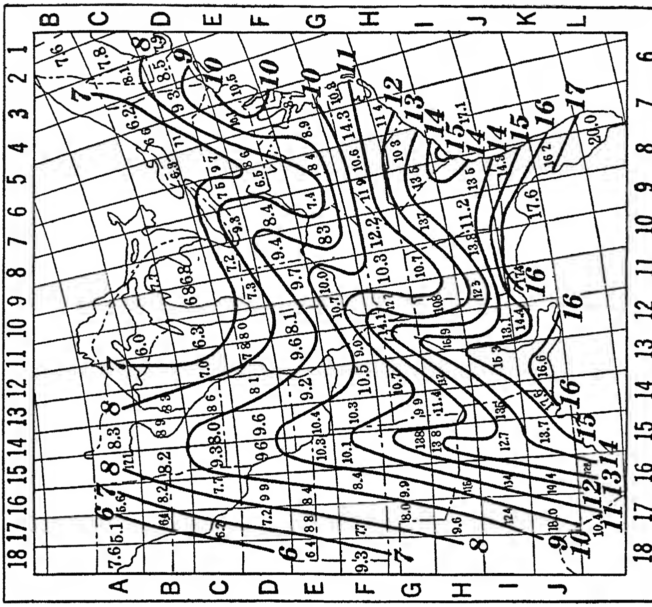


Isopluvial Chart for 100-Year Period and 4-Day Rainfall

From Reports of Miami Conservancy District



Isopluvial Chart for 100-Year Period and 5-Day Rainfall



Isopluvial Chart for 100-Year Period and 6-Day Rainfall

From Reports of Miami Conservancy District

Area Covered by Excessive Storms. — Frühling concluded from observations at Breslau, Germany, that the rate of precipitation 10,000 feet from the center of a storm was one half the maximum and that the reduction in intensity was along a parabolic curve. He deduced the formula (reduced to feet):

$$R = 1 - 0.0028\sqrt{L}$$

where R represents the ratio between intensity of precipitation at L feet from the center to that at the center. According to this formula, excessive rain storms cover an area about 15 miles in diameter.

The following data on this subject are taken from a paper entitled "The Distribution of Intense Rainfall" by Frank A. Marston of Metcalf & Eddy, Cons. Engrs., Boston, Mass., in Trans. Am. Soc. C. E., 1924, p. 535.

RAINFALL OF AUGUST 24, 1918, AT ST. LOUIS, MO.*

Straight line distances, in miles	Rain-gauge station	Total precipitation in hour of maximum intensity, 11 A.M. to 12:20 P.M., in inches	Time of beginning of heavy downpour, A.M.
$1\frac{3}{4}$	U. S. Weather Bureau	1.46	Extreme eastern gauge 11:30
$\frac{3}{4}$	613 North Garrison St.	3.60	" " " 11:20
$6\frac{5}{8}$ $1\frac{1}{2}$	St. Louis University.	2.64	" " " 11:10
1	Kingsley and Enright	0.55	" " " 10:57
$\frac{3}{4}$	Union and Patton...	0.39	" " " .....
$1\frac{3}{4}$	Shawmut and Ridge..	0 25	" " " .....
	University City... .	0.18	Extreme western gauge 10:55

* Data from Engineering News-Record, October 10, 1918, p. 672.

AVERAGE RATES OF PRECIPITATION AND AREAS COVERED, CAMBRIDGE, OHIO

Date	Time, period, in minutes	Average rate of precipitation, in inches per hour	Area covered, in acres	Area covered, in square miles	Maximum rate of precipitation, in inches per hour	Ratio: Average rate to maximum rate
July 16, 1914	90	4 70	518	0.81	4.73	0 99
		4.46	1440	2.25	4.73	0 94
		4.11	2682	4.19	4.73	0 87
		3.68	4320	6.75	4.73	0 78
		3 23	6522	10.19	4 73	0.68
		2 73	9517	14.87	4.73	0.58
		2 27	12,960	20.25	4.73	0 48
		1.76	18,195	28.43	4.73	0 37

AVERAGE INTENSITY OF PRECIPITATION AND AREA COVERED, BOSTON, MASS.
ESTIMATED FREQUENCY OF OCCURRENCE, 10 YEARS

Duration, 30 Min.		Duration, 45 Min.		Duration, 60 Min.	
Area, in acres	Average intensity of precipitation, in inches per hour	Area, in acres	Average intensity of precipitation, in inches per hour	Area, in acres	Average intensity of precipitation, in inches per hour
0	2.48	0	1.94	0	1.60
500	2.34	500	1.85	500	1.55
1000	2.26	1000	1.80	1000	1.52
1500	2.20	1500	1.76	1500	1.49
2000	2.15	2000	1.74	2000	1.47
3000	2.07	3000	1.69	3000	1.43
4000	1.98	4000	1.65	4000	1.40
5000	1.92	5000	1 61	5000	1.38

Estimating Probable Maximum Precipitation on Watersheds. —By superimposing storm maps upon maps of the watersheds of different streams in the region in which the storms occurred, giving due consideration to storm paths, a good estimate can be made of the probable maximum amount of precipitation which may be expected on the watershed in the given time.

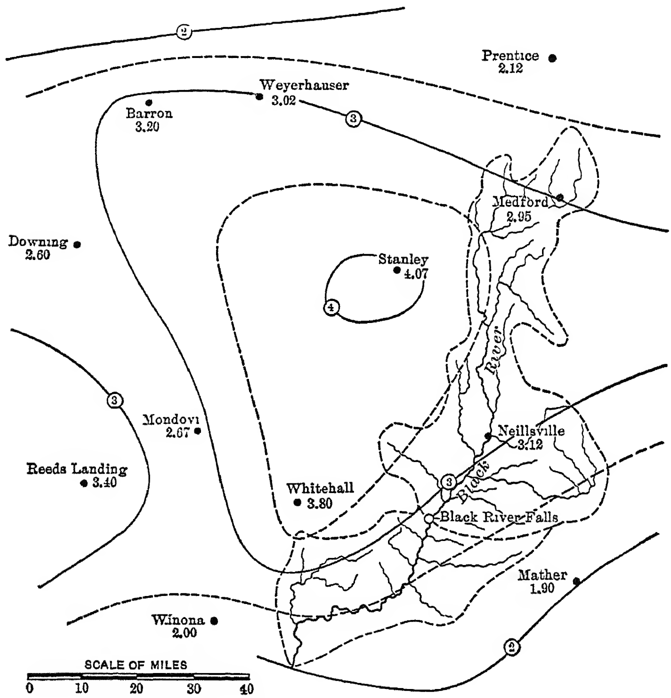


FIG. 129.—Map of Stanley, Wisconsin, Storm, October 6, 1911. Average Precipitation over Black River Watershed above Black River Falls, 3.00 ins.

For example, the Stanley, Wisconsin, storm of October 6, 1911, Fig. 129, when moved a little further to the east, Fig. 130, results in an increase in the 24-hour average precipitation on the watershed above Black River Falls from 3.00 to 3.69 inches. The Beaulieu, Minnesota, storm of July, 1909, would have caused an average precipitation of 6.1 inches over the watershed of the Black River above Black River Falls and 7.2 inches

over the watershed above Neillsville. The Merrill, Wisconsin, storm of July, 1912, would have resulted in an average precipitation over these watersheds of 4.8 inches and 6.4 inches, respectively. This Merrill storm, averaging 4.1 inches over the watershed of the Wisconsin River above Wausau caused a flood at Wausau which was 1.8 feet higher than the highest previous

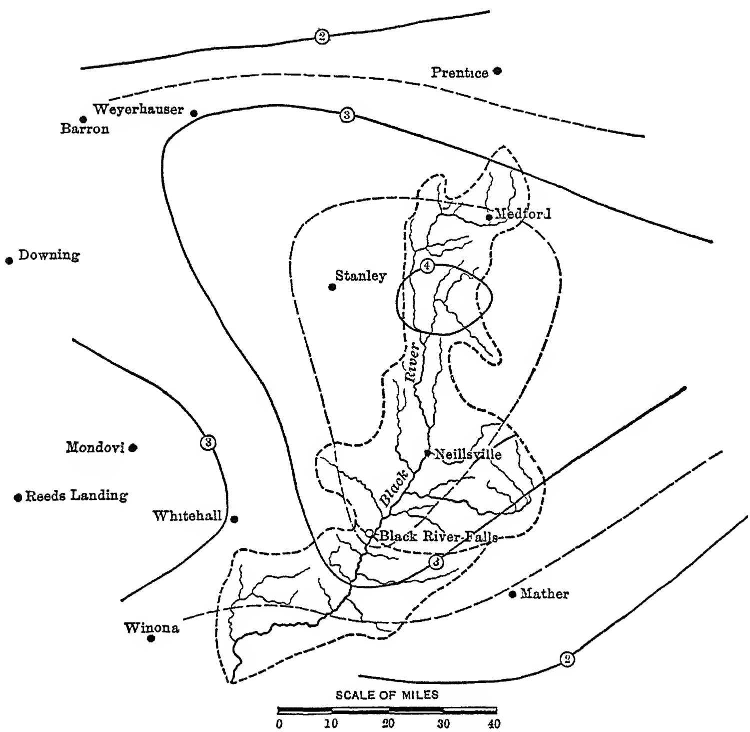


FIG. 130. — Stanley, Wisconsin, Storm of October 6, 1911, transposed. Average Precipitation over Black River Watershed above Black River Falls, 3.69 ins.

record, that of September, 1881. It is interesting to note, however, that notwithstanding this fact the Beaulieu, Minnesota storm of July, 1909, would have caused a still greater precipitation, *viz.*, 6.4 inches, over this watershed.

From a study of Wisconsin and Illinois rainfall, Stewart *

* Stewart, C. B., West. Soc. Engrs., 1913, p. 290.

concluded that once in about 50 years the following amounts of precipitation might be expected in the given time and over areas of from 500 to 2500 square miles.

PROBABLE MAXIMUM RAINFALL OCCURRING ABOUT ONCE IN FIFTY YEARS

Days	Inches rainfall over		
	500 sq. mi.	1000 sq. mi.	2500 sq. mi.
2	10	8	6
4	11	9	7
10	13	$11\frac{1}{2}$	10
30	15	14	13

Fig. 131 gives the precipitation in 2, 3 and 4 days in the state of Ohio during the storm of March, 1913. The data for the 2- and 4-day storms of this Figure are based upon Bulletin Z

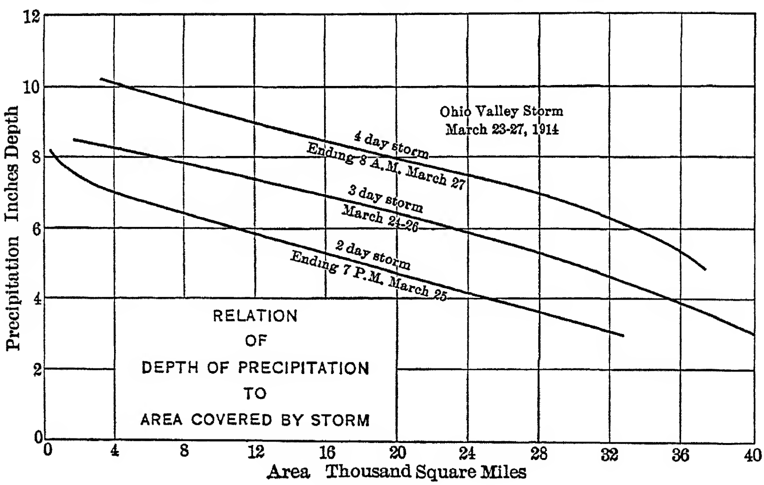


FIG. 131.

of the U. S. Weather Bureau; that for the 3-day storm is based upon Prof. Sherman's paper, "The Ohio Water Problem."

Morgan* gives the following rates of rainfall for the greatest recorded 1-, 2- and 3-day storms in the upper Mississippi valley.

* Morgan, Arthur E., Report to the Board of Directors of the Miami Conservancy District.

TABLE 10.—DEPTH IN INCHES OF THE GREATEST AVERAGE RAINFALL ON AREAS OF VARIOUS SIZE DURING NINE GREATEST RECORDED STORMS THAT HAVE OCCURRED IN THE UPPER MISSISSIPPI VALLEY*

(Arthur E. Morgan)

Storm	Center	Greatest 24-hour rainfall for area in square miles						Greatest 48-hour rainfall for area in square miles						Greatest 72-hour rainfall for area in square miles					
		1	500	1000	1500	2000	2500	1	500	1000	1500	2000	2500	1	500	1000	1500	2000	2500
1889, May 31–June 1	Pa.	8 4	7 6	7 3	7 3	7 2	7 2	9 8	9 1	8 8	8 6	8 4	8 2	.		..			.. ..
1900, July 14–16	Iowa	7.0	6 8	6 6	6 5	6 3	6 2	13 0	11 6	10 7	10 1	9 7	9 3	13 7	12 2	11 4	10 9	10 5	10 2
1903, Aug. 26–28	Iowa	11 2	10 7	10 0	9 5	9 0	8 7	14 7	11 7	10 8	10 2	9 7	9 2	. ..	.	.	.	..	...
1905, June 9, 10	Iowa	13 0	11 0	10 0	9 2	8 8	8 5	.							.				. .
1909, July 5–8	Kas.	9 7	8 0	7 2	6 5	6 1	5 7	9 7	8 3	7 7	7 2	6 8	6 5	11 2	10 2	9 7	9 4	9 2	9 0
1909, July 19–22	Mich.	10 7	9.2	7.8	7 0	6 4	6 0	11 0	9 8	8 7	7 9	7 4	7 0	12 8	9 2	8 6	8 3	8 0	7 8
1910, Oct. 4–6	So. Ill.	8.5	7.5	6 7	6.2	5 9	5 7	12 5	11 0	10 3	9 9	9 5	9 3	15 2	13 8	12 8	12 4	12 1	11 8
1913, Mch. 23–27	Ohio	7.0	6.7	6 5	6 3	6 2	6 1	9 5	8 7	8 4	8 3	8 2	8 1	10 2	9 7	9 4	9 2	9 1	9 0
1915, Aug. 17–20	Ark.	6.7	6.6	6 6	6 5	6 5	6 5	10 9	10 2	9 8	9 4	9 2	9 0	14 0	13 2	12 7	12 3	11 9	11 7

* See also pages 129, *et seq.*, 143 *et seq.*

Hourly Rates of Excessive Precipitation. — In municipal improvement work, particularly in the design of sewerage and drainage systems, and works for the collection of water running off from small watersheds, the amount of precipitation which may be expected in one or two hours, and in less than hourly periods of time, is of great importance. The frequency with which given rates of precipitation may be expected to recur should be the basis of design, but whether an installation which is designed to care for all rates of precipitation that may be expected once in 1 year, or once in 10 or 100 years, or in any intermediate time interval, will best serve a given community, the engineer must determine in each individual instance. In the following pages, the author has summarized most of the available data relating to excessive precipitation in the United States east of the Rocky Mountains, and has presented a number of new formulas giving the amount and rates of precipitation from 5 to 120 minutes time which, on an average, will probably be exceeded once in intervals of from 1 to 100 years.

Most studies of rates of excessive precipitation, made heretofore, have been based upon an analysis of the records of single observation stations. In view of the irregular manner in which precipitation occurs, with respect to time, in any given locality, however, the records of a single station furnish a far less satisfactory basis for a conclusion regarding the frequency of given rates of excessive precipitation than the records of several stations in the same locality.

Intense rainstorms usually cover only a few square miles. Observation stations five or ten miles apart usually show about as much dissimilarity in the rates of excessive precipitation during intense rainstorms as stations 50 or 100 miles apart. As there are only about 200 Weather Bureau stations in the United States at which continuous records of precipitation are being secured, it is apparent that only a very few of the excessive rainstorms which actually occur, are being recorded.

In a few of the larger cities, of course, municipal organizations are maintaining a number of observation stations and are thus obtaining more complete data.

The records of adjacent observation stations well indicate the irregular manner in which excessive precipitation occurs. During the New York City storm of October 1, 1913, for example, (Fig. 132) twice as much rain fell in two hours at Borough Hall in the Borough of Richmond, than at the United States Weather Bureau station in the Borough of Manhattan, five miles away. It is safe to say that, taking the country as a whole, doubling the number of Weather Bureau observation stations would double the number of records of excessive precipitation obtained. For the same reason, the records of several stations in one region are virtually equivalent to a longer record at a single station. One record supplements the other, making a combined record which is far more representative of the rates of precipitation to be expected in the given region than the records of a single station.

Table 11 is a summary of the number of intense rainstorms during which given rates of precipitation have been exceeded at 43 United States Weather Bureau stations during the 19 years between 1896 and 1914. The extent to which the records of one station supplement those of another in the same part of the country is apparent from a study of this table. Stations with a disproportionate number of very excessive storms have usually had a deficiency of ordinary storms. Other stations that have experienced many short storms have had comparatively few long ones and *vice versa.*

In studying the observational data, the entire 1962 storms were first analyzed, and the greatest amount of precipitation which occurred at any time during the storm within a continuous period of 5, 10, 15, 30, 60, 100 and 120 minutes time was first determined. If a storm lasted only 60 minutes, the observed precipitation in that length of time was considered as also having fallen within 100 and 120 minutes time. While this is

virtually equivalent to assuming the precipitation which occurred in a given period of time as having been uniformly distributed over that time, nevertheless, it is believed that the estimates of the lengths of time required for the runoff from a given precipitation to reach various points of concentration in a sewer system, for example, are usually far more in error than the assumption of uniform, or progressively decreasing, rates of precipitation over periods of 15, 30, 60, or even 120 minutes of time. In other words, the author believes that the amount of precipitation which falls in a given period of time, even though not uniformly distributed over that time, nevertheless furnishes information which is fully as accurate as the other information and assumptions which enter into the computations of runoff into sewerage and drainage systems. The restriction of precipitation studies to storms of uniform rates does not appear warranted.

Table 12 gives the observational data for 100 typical intense storms in the United States east of the Rocky Mountains and Figs. 132 to 138 show graphically the precipitation during a few of the most exceptional storms, both in proper sequence of time as it actually occurred, and also when arranged in the order of maximum accumulated amounts of precipitation in the given time intervals.

Table 13 is a summary of these storms giving only the most exceptional rate of precipitation, together with similar records of the most exceptional earlier rainstorms.

From the records of the individual observation stations, the rate of precipitation which would probably be exceeded with frequencies of once in 1, 2, 5 and 10 years were first selected. Stations showing similar rates were placed in one group. These data appear in Table 14. From the combined records of all the stations in each group the rates of precipitation which would probably be exceeded in 1, 2, 5, 10, 25, 50 and 100 years were then determined and formulas worked up which best fitted the observational data. It was found that the precipitation varied

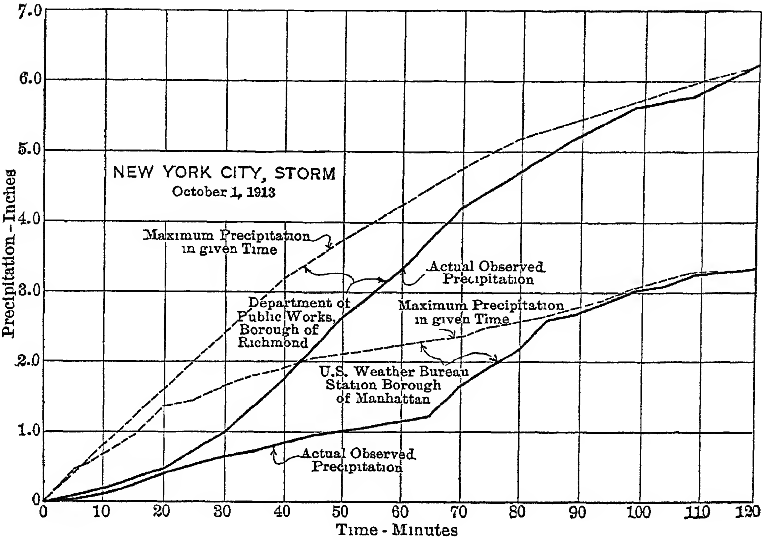


Fig. 132.

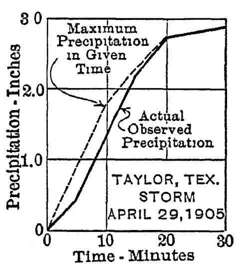


Fig. 133.

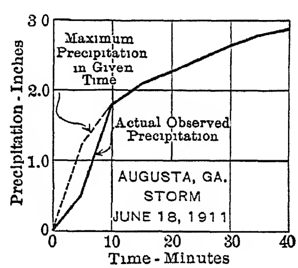


Fig. 134.

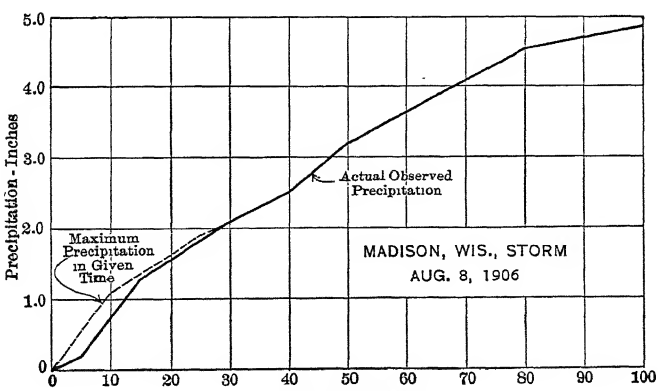


Fig. 135.

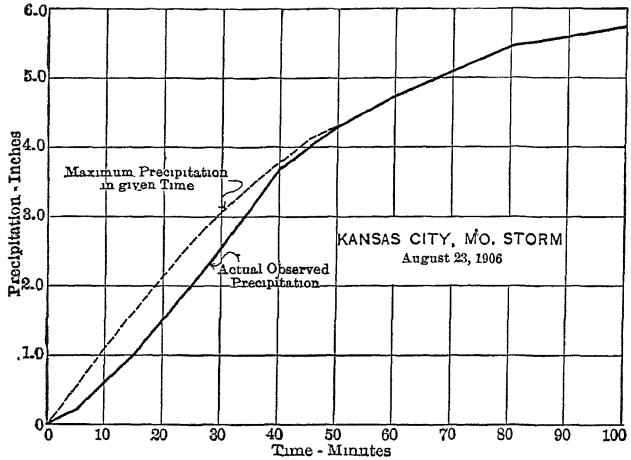


FIG. 136.

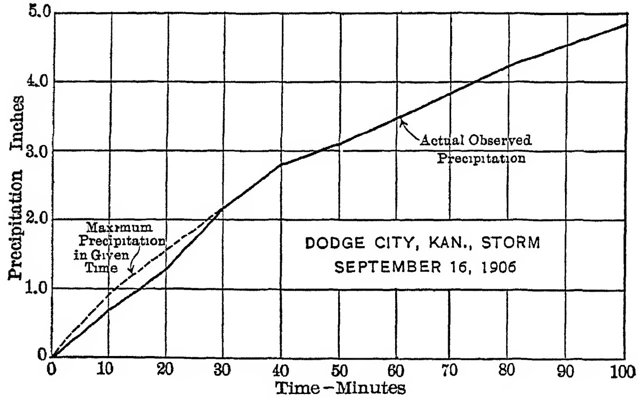


FIG. 137.

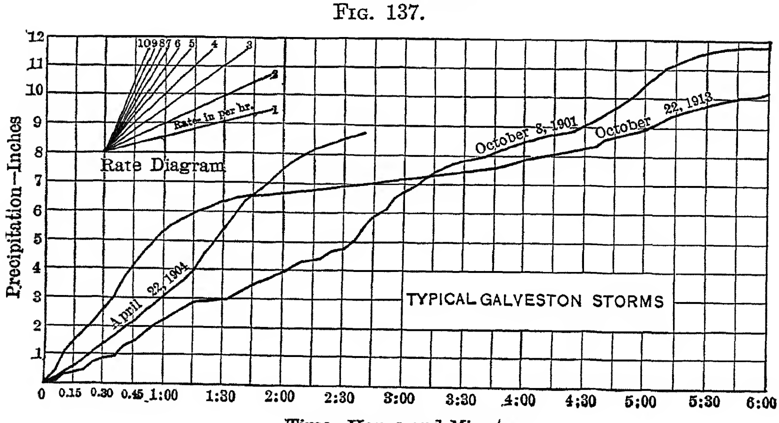


FIG. 138.

most nearly as the formula $Q = \frac{At}{t + B}$ where Q is the precipitation in inches, t the time in minutes, and A and B are constants. The frequency of different rates of precipitation varies approximately as $F^{0.2}$ where F represents the number of years between recurrences of rates of precipitation exceeding the given intensity. The exponent of F is less than .2 for 5- and 10-minute rates and greater for 100- and 120-minute rates, varying from about .15 to .3.

The author's formulas for the five groups of stations in the United States east of the Rocky Mountains, together with the precipitation to be expected in given time intervals of less than two hours, with frequencies of from once a year to once in 100 years, are given in Table 15. It is believed that the rates of precipitation here given furnish a better basis for design than those determined from the records of individual stations. Considering a long period of years, the amounts and rates of precipitation given by the formulas of this table will all be exceeded with equal frequency.

As the records of no stations used in this study of excessive precipitation extend over more than 19 years, it would obviously be impossible to determine, from the records of one station, the probable intensity of rates of precipitation which occurred with less frequency than once in 5 or 10 years. The combined records, however, indicate that some of the storms which have occurred within the last 20 years are not likely to recur at the same station with a greater frequency than once in 100 or more years.

For example, at Galveston, Texas, three storms have occurred in recent years which had an intensity which is to be expected only about once in 100 years. In all three of these storms the precipitation amounted to over 6 inches in two hours. The exceptional character of these storms is well indicated by the fact that no other storms occurred in the 19 years from 1896 to 1914 in which more than 4 inches of rain fell in two hours

The storm of August 8, 1906, at Madison, Wisconsin, was still more exceptional in character for this region. Over $4\frac{1}{2}$ inches of rain fell in two hours, yet, not another rainstorm occurred at this station during the period from 1905 to 1914 in which the precipitation exceeded $1\frac{1}{2}$ inches in two hours. It is probable that the storm of August 8, 1906, will not be equaled at this station in several hundred years.

Other storms in which rain fell at rates that will probably not be equaled, at the given stations, in several hundred years are the storms of August 23, 1906, at Kansas City, Mo., of October 13, 1913, at New York City, Borough of Richmond, of June 18, 1911, at Augusta, Ga., and of April 29, 1905, at Taylor, Texas.

Table 16 gives the principal formulas proposed in the past for the determination of rates of excessive precipitation in different sections of the United States. By reference to Table 15 the precipitation given by these formulas can be compared with that given by the author's formulas.*

Index Map. — Fig. 139 shows the location of Weather Bureau observation stations used in the rainfall studies just discussed and the boundaries of the areas to which the several formulas for frequency of excessive rates of precipitation apply. It is, of course, self-evident, that stations lying close to the border line between two areas share equally in the characteristics of those areas and mean values of the formulas applying to the two adjacent areas should be used. Stations lying farther from the border line naturally share in varying measure and weighted means should be used.

* The subject of excessive precipitation is also discussed in the following papers:

Maximum Rate of Precipitation at Boston for Various Frequencies of Occurrence, by Harrison P. Eddy of Metcalf & Eddy, Consulting Engrs., Boston, Mass., in Journal of the Boston Soc. of Civil Engineers, February, 1920.

Extraordinary Rainfall Flooded Portions of St. Louis, by W. W. Horner in Eng. News-Record, Oct. 10, 1918, p. 672.

The Frequency of High Rates of Rainfall, by Allen Hazen, Consulting Engineer, New York, Eng. News-Record, Nov. 24, 1921, p. 858.

Correlation of Maximum Rain Intensities for Long and Short Time Intervals, by Robert E. Horton, Monthly Weather Review, April, 1921.

The Probable Frequency of Given Rates of Rainfall, by the author, in Eng. News-Record, Dec. 29, 1921.

Correction of Precipitation Data to Maximum for Given Time Interval. — The excessive precipitation data published in the Annual Reports of the Chief of the Weather Bureau, from which Tables 11, 12, 13, 14 and 15 were prepared, give the accumulated precipitation at the end of every 5-minute interval from the beginning to the end of the period during which the rates were excessive. They do not give *all* of the precipitation during one and two-hour periods if the rates did not continue to be excessive to the end of the period. The criterion for "excessive" precipitation is that rain fell at the rate of 1 inch per hour, .5 inch in 30 minutes, .35 inch in 15 minutes or .25 inch in 5 minutes.

In consequence the 60-minute and 120-minute excessive rates determined from the published data are from 5 to 10 per cent low. It is also a fact that the published data do not give the actual maximum rates of precipitation during 5-minute intervals at any point of the storm, but only the maximum rate of precipitation during the particular 5-minute increments of time shown in the table of accumulated amounts. In consequence the 5-minute excessive rates determined from the published data are also about 10 per cent low. Intermediate rates are substantially correct, as might be expected.

During Jan., 1927, the author made a study of the original excessive precipitation records available in the offices of the U. S. Meteorologists at Minneapolis and St. Paul, Minnesota. The following table summarizes the results of this study.

EXCESSIVE PRECIPITATION AT ST. PAUL AND MINNEAPOLIS, MINNESOTA, 1905–1926

No. of excessive rates compared	Time interval, minutes	Maximum precipitation from unpublished data	Maximum precipitation from published data	Average correction required
55	5	.407	.374	+9%
58	10	.616	.600	+2½%
52	15	.777	.757	+2½%
55	30	1.05	1.03	+2%
52	60	1.36	1.30	+4½%
39	120	1.70	1.53	+11%

The study was limited to rates over .3 inch in 5 minutes; .45 in 10; .60 in 15; .75 in 30; .90 in 60 and 1.10 inches in 120 minutes.

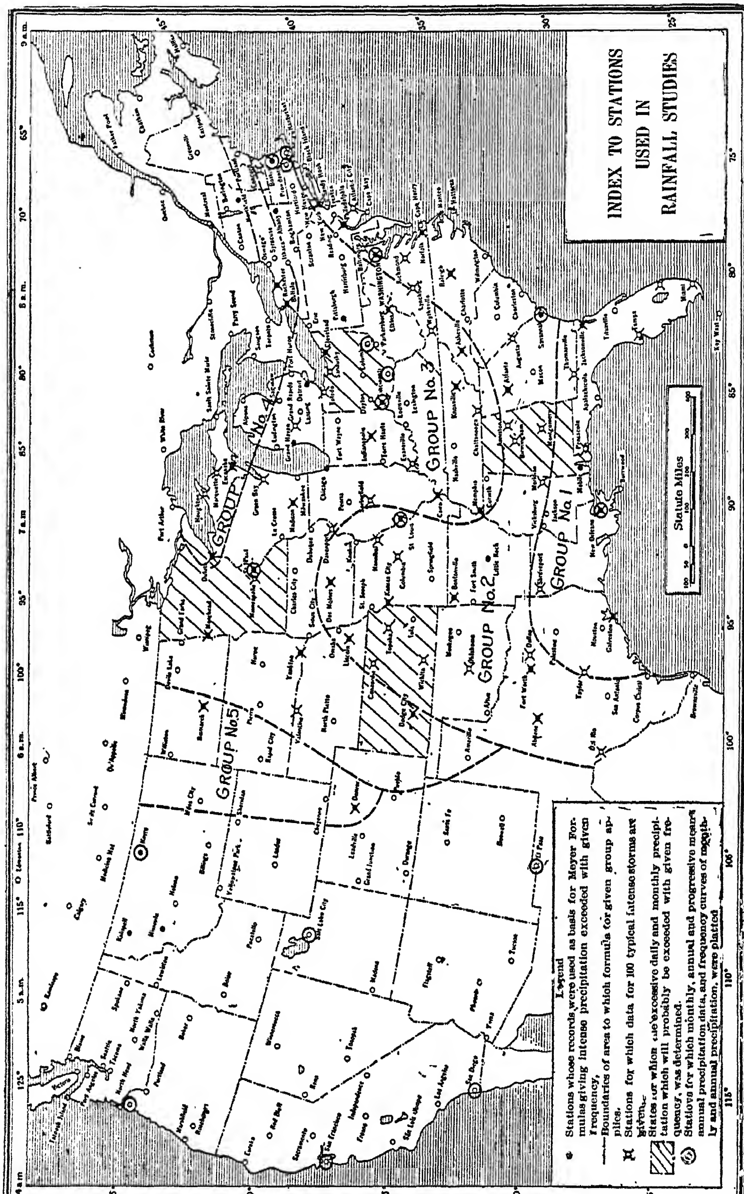

INDEX TO STATIONS
USED IN
RAINFALL STUDIES
GROUP No. 1
GROUP No. 2
GROUP No. 3
GROUP No. 4
GROUP No. 5
Statute Miles
Legend
Stations whose records were used as basis for Meyer Formulas giving intense precipitation exceeded with given frequency,
Boundaries of area to which formula for given group applies.
Stations for which data for 100 typical intense storms are given.
Stations for which the excessive daily and monthly precipitation which will probably be exceeded with given frequency, was determined.
Stations for which monthly, annual and progressive mean annual precipitation data, and frequency curves of monthly and annual precipitation, were platted

FIG. 139.

TABLE 11. — SUMMARY OF RECORDS OF INTENSE RAINSTORMS AT FORTY-THREE STATIONS — 1896–1914

Group No. 1 (57 Station-years)

Precipitation in 5 minutes	No. of storms of given intensity at				Total No. of storms exceeding given intensity
	Galveston	New Orleans	Jacksonville	Total	
0.40–0 44	5	12	11	28	84
0.45–0 49	5	4	7	16	56
0.50–0 54	8	5	9	22	40
0.55–0 59	2	5	3	10	18
0.60–0.69	3	1	3	7	8
0.70–0 79	....	....	1	1	1
In 10 minutes					
0.60–0 69	20	23	20	63	140
0.70–0.79	9	12	10	31	77
0.80–0.89	4	5	10	19	46
0.90–0.99	8	3	6	17	27
1.00–1.09	2	2	1	5	10
1.10–1.19	1	3	1	5	5
In 15 minutes					
0.80–0.89	12	18	11	41	130
0.90–0.99	15	13	8	36	89
1.00–1.09	2	8	9	19	53
1.10–1.19	3	2	5	10	34
1.20–1.39	7	4	3	14	24
1.40–1.59	3	2	4	9	10
1.60–1.79	....	1	....	1	1
In 30 minutes					
1.30–1.39	4	10	6	20	76
1.40–1.49	3	5	2	10	56
1.50–1.59	4	5	4	13	46
1.60–1.69	2	5	1	8	33
1.70–1.79	3	2	0	5	25
1.80–1.99	3	4	1	8	20
2.00–2.19	1	1	3	5	12
2.20–2 39	2	1	1	4	7
2.40–2.59	0	....	....	0	3
2.60–2.79	2	....	....	2	3
2.80–2.99	1	....	....	1	1
In 60 minutes					
1.70–1.79	....	2	0	2	60
1.80–1.99	8	7	6	21	58
2.00–2.19	5	4	3	12	37
2 20–2.39	6	1	3	10	25
2.40–2.59	2	4	0	6	15
2.60–2.79	0	1	0	1	9
2.80–2.99	0	1	1	2	8

TABLE 11.—SUMMARY OF RECORDS OF INTENSE RAINSTORMS AT FORTY-THREE STATIONS—1896–1914—(*Continued*)

Group 1 (57 Station-years)

Precipitation in 60 minutes	No. of storms of given intensity at				Total No. of storms exceeding given intensity
	Galveston	New Orleans	Jacksonville	Total	
3.00–3.24	1	....	1	2	6
3.20–3.39	1	....	....	1	4
3.40–3.59	0	....	....	0	3
3.60–3.79	0	....	....	0	3
3.80–3.99	0	....	....	0	3
4.00–4.49	2	....	....	2	3
4.50–4.99	0	....	....	0	1
5.00–5.49	1	....	....	1	1
In 100 minutes					
1.80–1.99	6	10	5	21	76
2.00–2.19	6	5	3	14	55
2.20–2.39	3	3	6	12	41
2.40–2.59	2	4	0	6	29
2.60–2.79	4	0	2	6	23
2.80–2.99	1	1	1	3	17
3.00–3.24	2	1	2	5	14
3.25–3.49	2	2	....	4	9
3.50–3.74	1	0	....	1	5
3.75–3.99	0	1	....	1	4
4.00–4.49	0	....	....	0	3
4.50–4.99	0	....	....	0	3
5.00–5.49	0	....	....	0	3
5.50–5.99	1	....	....	1	3
6.00–6.49	0	....	....	0	2
6.50–6.99	2	....	....	2	2
In 120 minutes					
1.90–1.99	2	3	1	6	63
2.00–2.19	6	4	4	14	57
2.20–2.39	4	4	5	13	43
2.40–2.59	2	4	1	7	30
2.60–2.79	4	0	0	4	23
2.80–2.99	1	1	2	4	19
3.00–3.24	1	1	2	4	15
3.25–3.49	1	1	0	2	11
3.50–3.74	2	0	0	2	9
3.75–3.99	1	1	1	3	7
4.00–4.49	0	1	....	1	4
4.50–4.99	0	....	....	0	3
5.00–5.49	0	....	....	0	3
5.50–5.99	0	....	....	0	3
6.00–6.49	1	....	....	1	3
6.50–6.99	1	....	....	1	2
7.00–7.99	1	....	....	1	1

TABLE 11.—SUMMARY OF RECORDS OF INTENSE RAINSTORMS AT FORTY-THREE STATIONS—1896–1914—(*Cont'd*)

Group No. 2 (260 Station-years)

Precipitation in 5 minutes	No. of storms of given intensity at New York	Philadelphia	Washington	Norfolk	Raleigh	Savannah	Atlanta	Little Rock	Fort Worth	Abilene	Bentonville	St. Louis	Kansas City	Lincoln	Des Moines	Total	Total No of storms exceeding given intensity
0.35–0.39	6	8	13	12	11	21	7	6	7	6	6	5	9	7	7	131	282
0.40–0.44	3	2	6	5	7	4	2	5	7	2	3	5	2	8	3	64	151
0.45–0.49	0	3	3	6	4	1	2	2	3	3	0	0	2	2	5	36	87
0.50–0.54	2	2	3	0	1	1	2	1	0	1	1	0	3	0	2	19	51
0.55–0.59	0	0	1	2	3	1	2	.	1	..	1	0	2	0	0	13	32
0.60–0.69	1	2	1	1	0	2	1			..	1	2	1	2	1	15	19
0.70–0.79	..	..	..	...	1		..		.	.		1	0		...	2	4
0.80–0.89	...	..	...	..	..		..	.	.	..	.	1	1		..	2	2
In 10 min.																	
0.50–0.54	3	4	8	10	15	16	10	11	13	2	7	8	15	9	3	134	515
0.55–0.59	4	9	8	13	10	17	6	8	5	6	2	2	11	4	10	115	381
0.60–0.69	5	7	17	16	13	17	13	4	14	7	8	5	8	9	8	151	266
0.70–0.79	2	3	4	5	5	1	2	6	6	3	1	5	3	5	4	55	115
0.80–0.89	1	2	3	3	4	0	1	1	2	1	1	2	2	2	3	28	60
0.90–0.99	1	3	1	2	2	3	1	..	.	...	0	2	1	0	1	17	32
1.00–1.09	0	...	1	...	1	1	1	...	.	..	0		3	0	0	7	15
1.10–1.19	0	...	0	...	0		..	..	...	.	1	..	1	1	1	4	8
1.20–1.39	1	..	1	...	1	.	.	..	..	...	. .	.	...	1	...	4	4
In 15 min.																	
0.65–0.69	7	2	9	8	6	17	4	13	8	6	3	5	8	4	10	110	489
0.70–0.79	3	8	10	16	12	20	10	11	11	7	7	5	15	13	8	156	379
0.80–0.89	3	8	13	11	12	7	11	6	8	4	2	3	5	4	3	100	223
0.90–0.99	2	3	3	3	4	5	4	1	6	0	3	6	5	6	5	56	123
1.00–1.09	1	1	1	4	3	0	2	3	2	1	0	3	1	1	1	24	67
1.10–1.19	0	0	1	2	3	2	0	...	3	2	0	0	2	1	2	18	43
1.20–1.39	1	3	2	1	2	2	2	...	...	...	0	0	0	0	2	15	25
1.40–1.59	0	...	2	...	0	...	...	...	...	..	1	0	2	1	...	6	10
1.60–1.79	1	...	..	...	1	...	..	...	...	..	..	..	1	1	...	4	4
In 30 min.																	
0.90–0.99	7	8	11	14	7	14	7	6	11	7	9	5	9	8	4	127	454
1.00–1.09	2	6	3	6	12	9	5	9	5	3	6	5	9	7	7	94	327
1.10–1.19	4	3	3	5	10	6	3	5	5	2	2	4	7	5	2	66	233
1.20–1.39	1	1	6	6	2	9	7	3	12	3	1	3	4	6	6	70	167
1.40–1.59	2	3	7	5	7	6	3	3	0	0	2	2	7	1	2	50	97
1.60–1.79	0	2	2	2	2	3	3	2	2	0	1	1	1	1	3	25	47
1.80–1.99	0	1	1	...	0	...	1	1	1	2	...	...	1	1	...	9	22
2.00–2.19	1	0	1	...	2	...	1	...	1	1	...	..	0	0	...	7	13
2.20–2.39	...	1	..	...	0	...	...	...	...	...	...	...	1	0	..	2	6
2.40–2.59	...	...	...	...	1	...	...	...	...	...	...	...	0	2	...	3	4
2.60–2.79	...	...	...	...	...	...	...	...	...	...	...	...	0	...	...	0	1
2.80–2.99	...	...	...	...	...	...	...	...	...	...	...	...	0	...	...	0	1
3.00–3.24	...	...	...	...	...	...	...	...	...	...	...	...	1	...	...	1	1

TABLE 11.—SUMMARY OF RECORDS OF INTENSE RAIN-STORMS AT FORTY-THREE STATIONS—1896–1914—(*Cont'd*)

Group No. 2 (260 Station-years)

Precipitation in 60 minutes	No. of storms of given intensity at																Total No. of storms exceeding given intensity
	New York	Philadelphia	Washington	Norfolk	Raleigh	Savannah	Atlanta	Little Rock	Fort Worth	Abilene	Bentonville	St. Louis	Kansas City	Lincoln	Des Moines	Total	
1.20–1.29	7	2	3	6	8	4	5	5	5	1	4	11	6	2	5	74	340
1.30–1.39	2	3	3	4	6	4	3	3	11	1	2	2	1	6	3	54	266
1.40–1.49	1	1	3	5	8	6	5	2	2	1	2	2	1	2	2	43	212
1.50–1.59	2	1	3	1	3	3	3	1	3	1	2	1	2	1	1	28	169
1.60–1.79	2	3	5	5	2	3	4	3	3	2	1	1	7	5	0	46	141
1.80–1.99	1	2	1	3	2	9	4	2	3	1	1	0	6	4	1	40	95
2.00–2.19	2	0	0	1	2	2	0	0	0	0	0	0	2	1	3	13	35
2.20–2.39	..	2	1	0	2	1	3	3	2	1	1	0	1	1	1	19	42
2.40–2.59	.	0	2	0	1	1	0	1	0	0	.	0	0	0	0	5	23
2.60–2.79	.	0	3	1	0	.	0	.	0	1	.	0	0	1	1	7	18
2.80–2.99	..	0	...	.	1		0	.	0	0	.	2	1	0	...	4	11
3.00–3.24	..	0	..		.	.	1	.	1	0	.	..	0	2	...	4	7
3.25–3.49	..	0	..		.	.	.	.	.	1	.	..	0	...	...	1	3
3.50–3.74	..	1	.		..	.	..	.	..	.	..	..	0	...	...	1	2
3.75–3.99	. .			.		.				..		..	0	...	...	0	1
4.00–4.49	...	...	.	..	. .	...	...	.	..	..	.	..	0	..	...	0	1
4.50–4.99	...	.	. .	...		.	..	.	.	.	.	...	1	...	...	1	1
In 100 min.																	
1.30–1.39	1	1	4	4	6	5	4	2	8	1	3	9	4	5	2	59	323
1.40–1.49	0	2	2	5	10	6	3	5	0	2	1	4	1	1	1	43	264
1.50–1.59	2	2	2	2	3	4	3	2	5	1	2	3	2	2	1	36	221
1.60–1.79	7	2	6	4	2	5	2	5	4	2	1	3	9	3	1	56	185
1.80–1.99	0	1	3	4	3	6	6	1	3	1	2	1	6	3	1	41	129
2.00–2.19	3	2	1	0	1	1	0	2	1	0	0	0	2	2	2	17	88
2.20–2.39	0	2	0	1	2	2	4	2	4	0	1	0	2	1	0	21	71
2.40–2.59	1	0	3	0	2	4	0	3	0	0	1	0	0	1	0	15	50
2.60–2.79	0	1	0	0	0	0	0	1	0	0	..	0	2	3	1	8	35
2.80–2.99	0	0	1	0	1	1	0	...	1	0	..	1	1	1	0	7	27
3.00–3.24	1	0	2	1	..	...	1	...	0	0	...	1	0	2	2	10	20
3.25–3.49	...	0	..	0	.	.	0	...	0	1	.	...	0	...	1	2	10
3.50–3.74	...	0	. .	0	..	...	0	. .	0	1	..	...	1	...	...	2	8
3.75–3.99	...	1	. .	0	..	...	0	..	1	0	..	...	0	...	...	2	6
4.00–4.49	...	.	. .	1	..	...	1	...	..	1	.	...	0	...	...	3	4
4.50–4.99	...	...	...	...	..	...	...	..	..	..	...	...	0	...	...	0	1
5.00–5.49	..	..	...	...		...	..	.	.	..	...	0	...	...	0	1
5.50–6.00	...	..	...	...		...	...	...	...	..	..	...	1	...	...	1	1
In 120 min.																	
1.40–1.49	0	2	3	5	9	6	3	3	0	1	1	3	1	1	1	39	265
1.50–1.59	1	2	2	1	3	4	3	3	4	2	2	4	1	2	1	35	226
1.60–1.79	5	2	6	5	3	5	2	5	5	2	1	2	8	3	1	55	191
1.80–1.99	2	0	2	4	3	5	5	2	3	1	2	3	8	3	1	44	136
2.00–2.19	3	1	1	0	1	2	0	2	1	0	0	0	2	2	2	17	92
2.20–2.39	1	2	1	1	2	2	5	2	3	0	1	0	2	1	0	23	75
2.40–2.59	0	1	3	0	2	3	0	2	1	0	0	0	0	0	0	12	52
2.60–2.79	1	1	0	0	0	1	0	0	0	0	0	0	0	1	1	5	40
2.80–2.99	0	0	1	0	1	0	0	0	1	0	0	1	1	3	0	8	35
3.00–3.24	0	0	1	0	..	1	1	2	0	0	0	1	0	2	1	9	27
3.25–3.49	1	0	1	1	..	..	0	...	0	0	1	...	1	1	2	8	18
3.50–3.74	...	0	..	0	...	..	0	...	0	1	...	..	2	...	...	3	10
3.75–3.99	...	0	..	0	..	..	0	..	0	1	...	...	0	...	...	1	7
4.00–4.49	...	1	...	0	..	...	1	...	1	1	...	...	0	...	...	4	6
4.50–4.99	...	...	...	1	...	...	..	...	...	...	...	...	0	...	...	1	2
5.00–5.49	...	...	...	...	...	..	..	...	...	...	...	...	0	...	...	0	1
5.50–5.99	...	...	...	...	...	..	...	...	...	...	...	...	1	...	...	1	1

TABLE 11.—SUMMARY OF RECORDS OF INTENSE RAINSTORMS AT FORTY-THREE STATIONS.—1896–1914—(*Cont'd*)

Group No. 3 (317 Station-years)

Precipitation in 5 minutes	No. of storms of given intensity at																				Total No. of storms exceeding given intensity
	Boston	Albany	Pittsburg	Elkins	Asheville	Knoxville	Memphis	Cairo	Indianapolis	Cincinnati	Cleveland	Detroit	Grand Haven	Chicago	Madison	St. Paul	Moorhead	Yankton	Dodge	Total	
0 35-0 39	2	5	2	5	8	8	5	4	10	2	3	7	1	7	4	4	1	4	3	85	185
0 40-0 44	1	3	4	4	2	1	1	1	4	1	1	4	2	1	0	3	0	2	3	38	100
0 45-0 49	0	2	0	1	3	3	1	1	1	2	0	3	..	1	0	6	0	1	4	29	62
0 50-0 54	0	0	1	1	0		0	1	3	1	2	1		1	0	1	0	2	2	16	33
0 55-0 59	1	2	1	1	1		0	.	0		0			2	1	1	0		1	11	17
0 60-0.69	.		.	..	0	.	0	.	1		1	.	.				1		.	3	6
0 70-0 79	.				1		1		.		1	..	...			.			..	3	3
0 80-0.89		.	.				.		..		.		..	.					..	..	....
In 10 min.																					
0 50-0.54	2	5	2	5	3	6	10	10	7	4	4	4	3	5	4	5	2	11	3	95	329
0 55-0 59	0	6	3	4	7	3	6	5	6	4	1	3	4	2	0	3	2	8	2	69	234
0 60-0 69	2	3	5	10	5	5	3	3	11	3	7	8	0	6	3	8	1	3	5	91	165
0 70-0 79	1	1	1	3	2	1	2	2	3	2	2	5	1	2	0	4	0	2	4	38	74
0 80-0 89	0	4	0	1	3	2	0	0	2	0	0	.	.	2	0	0	0	1	1	16	36
0 90-0 99	1	.	1	.	1		1	1	2	1	1	..	.	1	0	1	0	1	2	14	20
1 00-1 09		.	.	.	.	.	..	.	1		2	...	..	..	1	.	1		1	6	6
In 15 min.																					
0 65-0 69	1	2	0	4	2	3	8	5	5	1	3	5	0	2	0	2	0	2	4	49	268
0 70-0 79	2	3	5	5	6	5	7	8	4	4	4	7	3	4	2	6	4	7	5	91	219
0 80-0 89	1	2	1	3	3	1	1	2	11	1	5	3	4	4	2	7	2	3	2	58	128
0 90-0 99	0	2	1	1	3	2	4	2	4	2	0	4	..	3	0	0	0	2	4	34	70
1 00-1 09	1	1	0	3	1	2	.	1	4	0	1	...	...	1	0	0	0	0	2	17	36
1 10-1.19	..	1	1	..	1	0	..	0	0	0	1	...	...	1	0	1	0	1	2	9	19
1 20-1 39	...	..	...		..	1	.	1	1	1	0	...	....	..	1	1	1	1	1	5	10
1 40-1 59	...	..	...	.	.	...	.	..	...	.	1	.	...	...	..	..	..	...	..	1	1
In 30 min.																					
0.90-0.99	2	2	2	1	5	2	5	6	6	4	0	0	1	6	6	4	2	5	7	66	250
1 00-1.09	1	3	3	3	4	3	8	4	5	3	2	2	1	2	0	4	0	5	6	59	184
1 10-1.19	2	1	2	3	5	0	3	3	6	0	2	3	0	2	1	3	1	2	4	43	125
1.20-1.39	0	1	0	2	1	3	1	5	5	0	4	4	2	5	0	2	2	4	6	47	82
1 40-1.59	1	1	1	1	0	2	1	2	0	2	1	1	1	1	0	3	1	0	3	22	35
1.60-1 79	...	...	..	0	0	1	...	1	0	1	1	...	....	...	0	0	..	2	0	6	13
1.80-1.99	..	...	.	1	0	...	..	...	1	0	...	...	....	...	0	0	..	..	0	2	7
2.00-2.19	...		.	...	1	..	...	...	..	0	...	...	....	...	1	1	...	...	0	3	5
2.20-2 39	...	...	.	..	...	...	...	...	..	1	...	...	....	...	...	...	...	...	1	2	2

TABLE 11. — SUMMARY OF RECORDS OF INTENSE RAINSTORMS AT FORTY-THREE STATIONS. — 1896–1914 — (*Cont'd*)

Group No. 3 (317 Station-years)

Precipitation in 60 minutes	No. of storms of given intensity at																			Total No. of storms exceeding given intensity
	Boston	Albany	Pittsburg	Elkins	Asheville	Knoxville	Memphis	Cairo	Indianapolis	Cincinnati	Cleveland	Detroit	Grand Haven	Chicago	Madison	St. Paul	Moorhead	Yankton	Dodge	Total	
1.20-1 29	2	0	0	1	0	2	3	3	1	3	3	2	3	3	0	3	2	1	5	37	175
1 30-1 39	0	0	1	1	2	3	2	4	2	0	1	2	2	3	0	2	1	2	5	33	138
1 40-1 49	0	2	2	1	0	2	3	1	2	1	0	1	0	2	1	2	0	3	3	26	105
1 50-1 59	2	0	0	0	2	0	1	3	3	0	1	0	2	1	0	3	0	1	2	21	79
1 60-1 79	2	0	2	1	1	0	1	1	2	1	3	2		2	0	1	2	3	3	27	58
1 80-1 99		1		1	0	2	1	2	0	0		0			0	1	1	1	1	11	31
2 00-2 19				1	0			0	1	2		1			0	1		1	1	8	20
2 20-2 39				1	0			0	0	1		0			0	1			1	4	12
2 40-2 59					0			1	0			1			0	1			0	3	8
2 60-2 79					1			0	1						0				0	2	5
2 80-2 99								0							0				0	0	3
3 00-3 24								1							0				0	1	3
3 25-3 49															0				1	1	2
3 50-3 74															1					1	1
In 100 min.																					
1 30-1 39	3	0	2	1	2	3	1	4	1	0	1	1	2	2	0	1	1	3	7	35	157
1.40-1 49	0	1	2	1	0	2	2	1	2	2	0	1	0	2	1	2	1	2	3	25	122
1 50-1 59	3	0	0	0	1	0	2	1	4	0	1	0	2	0	0	2	1	1	1	19	97
1 60-1 79	1	0	2	1	1	0	1	0	2	2	2	1		3	0	2	1	2	3	24	78
1 80-1 99	1	2		0	0	3	4	1	1	0	0	3		1	0	2	2	3	0	23	54
2 00-2 19				1	0			3	0	1	1	0			0	1		1	0	8	31
2 20-2 39				1	1			1	1	1		0			0	2			1	8	23
2 40-2 59				0	0			1	0	1		0			0	0			1	3	15
2 60-2 79				0	1			1	0			2			0	0			1	5	12
2 80-2 99				0				0	1						0	1			0	2	7
3 00-3 24				1				0							0				1	2	5
3 25-3 49								0							0				0	0	3
3 50-3 74								1							0				0	1	3
3 75-3 99															0				0	0	2
4 00-4 49															0				0	0	2
4.50-4 99															1				1	2	2
In 120 min.																					
1.40-1 49	0	1	3	1	0	2	1	1	2	2	0	1	0	2	1	2	0	2	3	24	126
1 50-1 59	3	0	0	1	1	0	3	1	4	0	1	0	2	0	0	2	1	1	1	21	102
1.60-1.79	3	0	2	1	1	0	0	0	1	1	2	1		3	0	2	2	2	3	24	81
1.80-1 99	1	2		0	0	2	3	1	1	1	0	2		1	0	2	2	3	0	21	57
2.00-2.19				1	0	0	1	2	0	1	1	1			0	1		1	0	9	36
2.20-2 39				1	0	1	0	1	1	1		0			0	2			0	7	27
2.40-2.59				0	0		1	2	1	1		0			0	0			2	7	20
2.60-2 79				0	2			1	0			2			0	0			0	5	13
2 80-2 99				0				0	1						0	0			0	1	8
3.00-3 24				1				0							0	1			2	4	7
3 25-3 49								0							0				0	0	3
3.50-3 74								1							0				0	1	3
3.75-3 99															0				0	0	2
4 00-4 49															0				0	0	2
4.50-4.99															1				1	2	2

TABLE 11.—SUMMARY OF RECORDS OF INTENSE RAINSTORMS AT FORTY-THREE STATIONS — 1896–1914 — (*Cont'd*)
Group No. 4 (73 Station-years)

Precipitation in 5 minutes	No. of storms of given intensity at					Total No. of storms exceeding given intensity
	Duluth	Escanaba	Rochester	Buffalo	Total	
0.30–0.34	7	5	3	8	23	50
0.35–0.39	3	3	3	4	13	27
0.40–0.44	6	1	1	1	9	14
0.45–0 49	1	0	0	0	1	5
0 50–0 59	1	0	1	0	2	4
0 60–0.69	....	1	....	0	1	2
0.70–0 79	....	....	....	1	1	1
In 10 minutes						
0.45–0.49	9	1	1	4	15	52
0 50–0.59	6	4	3	5	18	37
0 60–0 69	0	0	6	3	9	19
0.70–0 79	5	1	....	2	8	10
0.80–0 89	0	0	....	....	0	2
0.90–0 99	1	0	....	....	1	2
1.00–1 09	....	0	....	....	0	1
1.10–1 19	....	0	....	....	0	1
1.20–1.39	....	1	....	....	1	1
In 15 minutes						
0.60–0 69	8	4	6	2	20	44
0.70–0.79	3	1	2	5	11	24
0 80–0 89	2	0	1	3	6	13
0 90–0 99	2	0	1	1	4	7
1.00–1 09	1	0	....	....	1	3
1.10–1.19	0	0	....	....	0	2
1.20–1 39	1	0	....	....	1	2
1.40–1.59	....	1	....	....	1	1
In 30 minutes						
0.75–0.79	3	3	3	2	11	47
0 80–0 89	4	5	1	2	12	36
0 90–0.99	2	0	1	0	3	24
1.00–1.09	4	1	1	2	8	21
1.10–1.19	1	0	1	3	5	13
1.20–1.39	0	0	1	2	3	8
1.40–1.59	2	0	0	....	2	5
1.60–1.79	1	1	1	....	3	3
In 60 minutes						
0.90–0.99	2	4	2	0	8	43
1.00–1.09	3	3	3	1	10	35
1.10–1.19	1	1	1	3	6	25
1.20–1–29	1	1	1	0	3	19
1.30–1.39	2	0	0	2	4	16
1.40–1.49	2	0	0	0	2	12
1.50–1.59	1	0	1	0	2	10
1.60–1.79	1	0	0	1	2	8
1.80–1.99	0	1	2	0	3	6
2.00–2.19	0	....	0	0	0	3
2.20–2.39	1	....	0	1	2	3
2.40–2.59	....	....	1	....	1	1

TABLE 11.—SUMMARY OF RECORDS OF INTENSE RAINSTORMS AT FORTY-THREE STATIONS — 1896–1914 — (*Cont'd*)

Group No. 4 (73 Station-years)

Precipitation in 100 minutes	No. of storms of given intensity at					Total No. of storms exceeding given intensity
	Duluth	Escanaba	Rochester	Buffalo	Total	
1.00–1.09	1	3	2	1	7	40
1.10–1.19	3	1	0	3	7	33
1 20–1 29	1	2	0	0	3	26
1.30–1 39	2	0	0	2	4	23
1.40–1 49	2	0	1	0	3	19
1.50–1.59	1	0	2	0	3	16
1.60–1.79	1	0	2	1	4	13
1.80–1 99	1	2	2	0	5	9
2 00–2.19	1	....	0	0	1	4
2 20–2 39	0	....	0	1	1	3
2 40–2 59	1	....	0	....	1	2
2.60–2 79	....	....	1	....	1	1
In 120 minutes						
1.10–1.19	3	1	0	3	7	33
1.20–1.29	1	1	0	0	2	26
1 30–1.39	2	0	0	2	4	24
1 40–1.49	2	1	1	0	4	20
1.50–1.59	1	0	2	0	3	16
1.60–1.79	1	0	0	1	2	13
1.80–1 99	0	2	3	0	5	11
2.00–2.19	2	....	1	0	3	6
2.20–2 39	0	....	0	1	1	3
2 40–2.59	1	....	0	....	1	2
2 60–2.79	....	....	1	....	1	1

Group No. 5 (38 Station-years)

Precipitation in 5 minutes	No. of storms of given intensity at			Total No. of storms exceeding given intensity
	Denver	Bismarck	Total	
0 30–0.34	3	1	4	23
0.35–0.39	3	5	8	19
0.40–0 44	3	1	4	11
0 45–0 49	0	1	1	7
0.50–0 54	3	2	5	6
0 55–0.59	0	....	0	1
0.60–0 69	0	....	0	1
0.70–0.79	0	....	0	1
0.80–0.89	1	....	1	1
In 10 minutes				
0.45–0.49	2	5	7	33
0.50–0.54	7	2	9	26
0.55–0 59	1	2	3	17
0.60–0.69	1	3	4	14
0.70–0.79	2	3	5	10
0.80–0.89	2	0	2	5
0.90–0.99	1	1	2	3
1.00–1.09	0	....	0	1
1.10–1.19	0	....	0	1
1.20–1.39	1	....	1	1

TABLE 11.—SUMMARY OF RECORDS OF INTENSE RAIN-STORMS AT FORTY-THREE STATIONS — 1896-1914 — (*Concl'd*)
Group No. 5 (38 Station-years)

Precipitation in 15 minutes	No. of storms of given intensity at			Total No of storms exceeding given intensity
	Denver	Bismarck	Total	
0.60–0.69	5	5	10	31
0.70–0 79	2	5	7	21
0.80–0 89	4	2	6	14
0.90–0 99	2	1	3	8
1.00–1 09	1	1	2	5
1.10–1.19	1	0	1	3
1.20–1.39	0	1	1	2
1.40–1 59	1	....	1	1
In 30 minutes				
0.85–0 89	3	1	4	26
0.90–0 99	2	5	7	22
1.00–1.09	3	3	6	15
1 10–1.19	1	2	3	9
1.20–1.39	3	1	4	6
1.40–1.59	0	0	0	2
1 60–1 79	1	0	1	2
1 80–1.99	....	0	0	1
2.00–2 19	....	0	0	1
2.20–2 39	....	1	1	1
In 60 minutes				
1.10–1.19	2	3	5	13
1.20–1.29	2	2	4	8
1.30–1.39	1	1	2	4
1.40–1.59	0	0	0	2
1.60–1.79	1	0	1	2
1.80–1.99	....	0	0	1
2.00–2.19	....	0	0	1
2.20–2.39	....	0	0	1
2.40–2.59	....	0	0	1
2.60–2.79	....	0	0	1
2.80–2 99	....	1	1	1
In 100 minutes				
1.20–1.29	2	2	4	9
1.30–1.39	1	1	2	5
1.40–1.59	0	0	0	3
1.60–1.79	1	1	2	3
1.80–1.99	....	0	0	1
2.00–2.19	....	0	0	1
2.20–2.39	....	0	0	1
2.40–2.59	....	0	0	1
2.60–2.79	....	0	0	1
2.80–2.99	....	1	1	1
In 120 minutes				
1.30–1.39	1	1	2	5
1.40–1.59	0	0	0	3
1.60–1.79	1	1	2	3
1.80–1.99	....	0	0	1
2.00–2.19	....	0	0	1
2.20–2.39	....	0	0	1
2.40–2.59	....	0	0	1
2.60–2.79	....	0	0	1
2.80–2.99	....	1	1	1

TABLE 12. — DATA FOR 100 TYPICAL INTENSE RAIN-STORMS — 1896 — 1914

No.	Station	Time in minutes													
		5	10	15	20	25	30	35	40	45	50	60	80	100	120
	Abilene, Texas, May 22, 1908														
1	Obs. precip.	0 35	0 52	0 82	1 06	1 42	1 77	2 10	2 41	2 56	2 60	2 70	3 17	4 17	4 42
	Increment	0 35	0 17	0 30	0 24	0 36	0 35	0 33	0 31	0 15	0 04	0 10	0 47	1 00	0 25
	Max. precip.	0 36	0 71	1 04	1 35	1 59	1 89	2 06	2 41	2 56	2 60	2 70	3 17	4 17	4 42
	Abilene, Texas, Oct 22, 1908														
2	Obs. precip.	0 06	0 16	0 41	0 71	0 80	0 89	1 05	1 35	1 70	1 92	2 27	2 50	3 29	3 94
	Increment	0 06	0 10	0 25	0 30	0 09	0 09	0 16	0 30	0 35	0 22	0 35	0 23	0 79	0 65
	Max. precip.	0 35	0 65	0 87	1 04	1 22	1 38	1 54	1 76	1 93	2 11	2 27	2 50	3 29	3 94
	Abilene, Texas, July 31, 1911														
3	Obs. precip.	0 24	0 70	1 03	1 36	1 69	2 02	2 32	2 76	3 01	3 14	3 46	3 65		....
	Increment	0 24	0 46	0 33	0 33	0 33	0 33	0 30	0 44	0 25	0 13	0 32	0 19	.	..
	Max. precip.	0 46	0 79	1 12	1 45	1 78	2 08	2 52	2 77	3 01	3 14	3 46	3 65	.	..
	Anniston, Ala., Sept. 5, 1906														
4	Obs. precip.	0 29	0 86	1 45	2 10	2 65	2 97	3 25	3 43	3 50	3 56	3 60		.	....
	Increment	0 29	0 57	0 59	0 65	0 55	0 32	0 28	0 18	0 07	0 06	0 04		.	....
	Max. precip.	0 65	1 24	1 81	2 36	2 68	2 97	3 25	3 43	3 50	3 56	3 60	.	..	....
	Anniston, Ala., April 22, 1909														
5	Obs. precip.	0 24	0 36	0 64	1 07	1 42	1 67	1 95	2 09	2 17	2 29	2 56	2 84	...	....
	Increment	0 24	0 12	0 28	0 43	0 35	0 25	0 28	0 14	0 08	0 12	0 27	0 28	. ..	...
	Max. precip.	0 43	0 78	1 06	1 31	1 59	1.73	1 95	2 09	2 17	2 29	2 56	2 84	....	...
	Asheville, N. C., Aug. 12, 1911														
6	Obs. precip.	0 38	0 75	1 10	1 45	1 79	2 12	2 40	2 53	2 65	2 67	.	...	..	....
	Increment	0 38	0 37	0 35	0 35	0 34	0 33	0 28	0 13	0 12	0 02	..	.	....	....
	Max. precip.	0 38	0 75	1 10	1 45	1 79	2 12	2 40	2 53	2 65	2 67		...	....	....
	Asheville, N. C., June 12, 1914														
7	Obs. precip.	0 70	0 89	0.91	0 94	1 02	1 09	1 12	..	.	..	...	...	....	....
	Increment	0 70	0 19	0 02	0 03	0 08	0 07	0 03	.	..	.	...	....	....	....
	Max. precip.	0 70	0 89	0 91	0 94	1 02	1 09	1 12	..	.	...	..	....	....	....
	Atlanta, Ga., July 23, 1898														
8	Obs. precip.	0 27	0 67	0 90	1 19	1 47	1 74	1 85	1.96	2.02	2 09	2 29	3 38	4 03	4.32
	Increment	0 27	0 40	0 23	0 29	0 28	0 27	0 11	0 11	0 06	0 07	0 20	1.09	0 65	0 29
	Max. precip.	0.40	0 67	0 92	1 20	1 47	1.74	1.85	1.96	2 02	2 09	2 29	3.38	4.03	4 32
	Atlanta, Ga., Mar. 15, 1912														
9	Obs. precip.	0 13	0 25	0 40	0 63	0 86	1 05	1 54	1 66	1 78	1 88	2 26	2.78	3 37	...
	Increment	0 13	0 12	0 15	0 23	0 23	0 19	0 49	0 12	0 12	0 10	0 38	0 52	0.59	....
	Max. precip.	0.49	0 68	0.91	1 14	1 29	1 41	1.54	1 66	1.86	2 01	2 26	2.78	3.37	....

TABLE 12. — DATA FOR 100 TYPICAL INTENSE RAIN-STORMS — 1896–1914 — (*Continued*)

No.	Station	Time in minutes													
		5	10	15	20	25	30	35	40	45	50	60	80	100	120
	Atlanta, Ga., Aug 20, 1914														
10	Obs precip. .	0 50	0 90	1 02	1 33	1 67	1 96	2 44	2 89	3 03	3 19	.		.	.
	Increment. .	0 50	0 40	0 12	0 31	0 34	0 29	0 48	0 45	0 14	0 16				..
	Max precip..	0 50	0 93	1 22	1 56	1 87	2 01	2 44	2 89	3 03	3 19		..		...
	Atlantic City, N. J., May 31, 1906														
11	Obs. precip. . .	0 83	1 19										..		...
	Increment ...	0 83	0 36												...
	Max. precip. . .	0 83	1 19			.							.		...
	Augusta, Ga., June 18, 1911														
12	Obs. precip.	0 56	1 80	2 11	2 26	2 46	2 65	2 77	2 88	.					. .
	Increment . . .	0 56	1 24	0 31	0 15	0 20	0 19	0 12	0 11						.
	Max. precip. . .	1 24	1 80	2 11	2 26	2 46	2 65	2 77	2 88						...
	Baltimore, Md., Aug 25, 1911														
13	Obs. precip. .	0 19	0 75	1 30	1 74	2 22	2 30	.			.			.	...
	Increment . .	0 19	0 56	0 55	0 44	0 48	0 08	.				.			...
	Max. precip. .. .	0 56	1 11	1 55	2 03	2 22	2 30								...
	Bentonville, Ark., April 23, 1908														
14	Obs. precip.	0 08	0 14	0 40	1 04	1 59	1 76	1 81	1 88				.		..
	Increment .. .	0 08	0 06	0 26	0 64	0 55	0 17	0 05	0 07			.		.	...
	Max. precip. .	0 64	1 19	1 45	1 62	1 68	1 76	1 81	1 88	..	.		.	.	....
	Birmingham, Ala., July 24, 1910														
15	Obs. precip. .. .	0 29	0 57	0 86	1 17	1 60	1 87	1 97	1 99	2 01	2 08	2 23	2 37	.	...
	Increment	0 29	0 28	0 29	0 31	0 43	0 27	0 10	0 02	0.02	0 07	0 15	0 14	. .	...
	Max. precip. ...	0 43	0 74	1 03	1 31	1 60	1 87	1 97	1.99	2 01	2 08	2 23	2 37	.	...
	Bismarck, N. D., Aug. 9, 1909														
16	Obs. precip..	0 14	0 47	0.92	1 20	1 47	1 89	2 40	2 73	2 94	2 99	..	..	...	...
	Increment.... . .	0 14	0 33	0 45	0 28	0 27	0 42	0 51	0 33	0.21	0 05	..	.	.	..
	Max. precip...	0 51	0 93	1 26	1 53	1 93	2.26	2 58	2 80	2 94	2 99	...	..	...	...
	Buffalo, N. Y., Mar. 20, 1897														
17	Obs. precip.	0 79	..	..	. .	. ..	.. .	..	.	...	....	..	.	...	....
	Increment	0 79	...	...	...	...	...	.	....	...	...	...	.	...	....
	Max precip.	0 79	. .	...	..	..	. .	..	..	..	. .	..	.	...	....
	Cairo, Ill., June 28, 1905														
	Obs. precip..........	0 07	0.16	0 22	0 26	0 30	0 34	0 37	0 46	0 71	1 05	.	. .	....	....
	Increment	0 07	0 09	0 06	0 04	0 04	0 04	0 03	0.09	0 25	0 34	. .	...	...	....
18	Max. precip......... .	0 40	0 70	0 94	1 17	1 43	1.67	1 86	2 02	2 29	2 56	.	. .	...	....
	Cont. (50 min.+)														
	Obs. precip..........	1 32	1 59	1 75	1 99	2 25	2.48	2 72	3 12	3 42	3 61	...	....	....	....
	Increment...........	0 27	0 27	0 16	0 24	0.26	0 23	0 24	0 40	0.30	0 19	..	...	...	....
	Max. precip....... ..	2 90	3.15	3 24	3 27	3 31	3.35	3 39	3.45	3.54	3 61	..	....	....	...

TABLE 12. — DATA FOR 100 TYPICAL INTENSE RAIN-STORMS — 1896–1914 — (*Continued*)

No.	Station	Time in minutes													
		5	10	15	20	25	30	35	40	45	50	60	80	100	120
	Cairo, Ill., July 30, 1913														
19	Obs. precip.	0 46	0 91	1 32	1 54	1 66	1 76	1 85		.	.		.	..	...
	Increment.. .	0 46	0 45	0 41	0 22	0 12	0 10	0 09							...
	Max. precip.	0 46	0 91	1 32	1 54	1 66	1 76	1 85		..	.				...
	Chattanooga, Tenn., Aug. 17, 1912														
20	Obs. precip. . .	0 25	0 48	0 78	1 23	1 46	1 80	2 10	2 22	2 27					....
	Increment	0 25	0 23	0 30	0.45	0 23	0 34	0 30	0 12	0 05					....
	Max. precip.	0 45	0 75	0 98	1 32	1 62	1 85	2 10	2 22	2 27	.		.		...
	Chattanooga, Tenn., Aug 22, 1912														
21	Obs. precip . ..	0 51	0 71	0 78	0 84	1 04	1 33	1 84	2 30	2 46	..	. .			....
	Increment . . .	0 51	0 20	0 07	0 06	0 20	0 29	0 51	0 46	0 16				.	...
	Max. precip	0 51	0 97	1 26	1 46	1 62	1 68	1 84	2 30	2 46	..		.		....
	Cincinnati, Ohio, May 20, 1902														
22	Obs. precip.. .. .	0 42	0 75	1 17	1 71	2 13	2 28	2 30	.		.	.			...
	Increment . .	0 42	0 33	0 42	0 54	0 42	0 15	0 02	. .		.	.	.		...
	Max. precip.	0 54	0 96	1 38	1 71	2 13	2 28	2 30	..		.	. .	.		...
	Cleveland, Ohio, Aug. 20, 1901														
23	Obs. precip... . .	0 37	1 04	1 46	1.77	1 78						.	....	...	..
	Increment	0 37	0 67	0 42	0 31	0 01	.					.	...	.	..
	Max. precip..	0 67	1 09	1 46	1 77	1 78				.		..	..	..	..
	Cleveland, Ohio, Aug. 29, 1903														
24	Obs. precip..... . .	0 78	1 04	1 06	1 09	1 17				..		.	.	...	..
	Increment.... . .	0 78	0 26	0 02	0 03	0 08		.	.	.			.	...	..
	Max. precip.. .	0 78	1 04	1 06	1 09	1 17	..			.	.	.	..	..	..
	Columbia, Missouri, June 29, 1909														
25	Obs. precip..... .	0.14	0 43	0 79	1 01	1 24	1 44	1 77	1 88	2 02	2 30	2 73	2.84	...	...
	Increment	0 14	0 29	0 36	0 22	0 23	0 20	0 33	0 11	0 14	0 28	0 43	0 11	...	...
	Max. precip...	0 36	0 65	0 87	1 10	1 34	1 63	1 77	1 88	2 16	2.38	2 73	2.84	....	....
	Concord, N. H., July 7, 1907														
26	Obs. precip.......	0 09	0 30	0 60	1 09	1 60	2.15	2 48	2.69	...	...	...	....	...	....
	Increment	0 09	0 21	0 30	0 49	0 51	0.55	0 33	0 21	. .	...	...	....	....	...
	Max. precip..	0 55	1 06	1 55	1 88	2 18	2.39	2.60	2 69	....	....	....	....	....	....
	Concordia, Kan., Aug. 26, 1908														
27	Obs. precip...........	0 10	0 41	0.83	1 36	1 78	2.09	2 23	2 35	2 43	....	....	....	....	....
	Increment	0.10	0 31	0 42	0 53	0.42	0.31	0 14	0.12	0 08	....	....		...	....
	Max. precip...........	0 53	0.95	1.37	1.68	1 99	2.13	2 25	2.35	2 43	....	....		...	....

TABLE 12. — DATA FOR 100 TYPICAL INTENSE RAINSTORMS — 1896–1914 — (*Continued*)

No.	Station	Time in minutes 5	10	15	20	25	30	35	40	45	50	60	80	100	120
	Dallas, Texas, Sept. 22, 1914														
28	Obs precip.	0 07	0 41	0 75	1 37	1 56	1 79	1 88	..	.	...	.	.	. .	...
	Increment	0 07	0 34	0 34	0 62	0 19	0 23	0 09		.	..	.	.	. .	...
	Max. precip.	0 62	0 96	1 30	1 49	1 72	1 81	1 88	. .	..	..	..	.	.	. .
	Davenport, Iowa, July 14, 1910														
29	Obs. precip.	0 38	0 92	1 38	1 59	1 61	1 62	1 73	1 82	.	..	..	.	.. .	.. .
	Increment	0 38	0 54	0 46	0 21	0 02	0 01	0 11	0 09	.	.	.	...	....	...
	Max. precip.	0 54	1 00	1 38	1 59	1 61	1 62	1 73	1 82		.	..	...	.. .	...
	Del Rio, Texas, July 2, 1914														
30	Obs precip.	0 08	0 18	0 36	0 56	0 84	0 99	1 10	1 32	1 45	1 65	2 13	2.93	3 31	3 56
	Increment	0 08	0 10	0 18	0 20	0 28	0.15	0 11	0 22	0 13	0 20	0 48	0 80	0 38	0 25
	Max. precip.	0 28	0 48	0 68	0 88	1 08	1 28	1 48	1 61	1 83	1 94	2 37	2 93	3 31	3 56
	Denver, Colo., July 14, 1912														
31	Obs. precip.	0 32	1 19	1 52	1 62	1 67	1 72			..	.	.	....	...	....
	Increment	0 32	0 87	0 33	0 10	0 05	0 05	..	.	..	.	...	. .	....	....
	Max. precip.	0 87	1 20	1 52	1 62	1 67	1 72		.	.	..	..	....	...	....
	Des Moines, Iowa, July 15, 1907														
32	Obs. precip.	0 11	0 28	0 50	0 85	1 18	1 41	1 62	1 80	1 90	2 01	2 14	2 95	3 29	. ..
	Increment	0.11	0 17	0 22	0.35	0 33	0 23	0 21	0 18	0 10	0 11	0 13	0.81	0 34	....
	Max. precip.	0 35	0 68	0 91	1 13	1 34	1 52	1 69	1 80	1 90	2 01	2 14	2 95	3.29	.. .
	Dodge City, Kan., Sept. 16, 1906														
33	Obs. precip.	0 35	0 71	0 96	1 30	1 77	2 21	2 50	2 81	2 95	3.11	3 47	4 27	4.85	...
	Increment	0 35	0 36	0 25	0 34	0 47	0 44	0 29	0 31	0 14	0.16	0 36	0 80	0 58	....
	Max. precip.	0 47	0 91	1 25	1 54	1 86	2 21	2.50	2 81	2 95	3 11	3.47	4 27	4 85	....
	Dodge City, Kan., July 17, 1911														
34	Obs. precip.	0 15	0.28	0.39	0 90	1 41	1 55	1.63	1 66	1.71	1.79	1.93	2 51	2 73	3.12
	Increment	0.15	0.13	0.11	0 51	0 51	0 14	0.08	0 03	0 05	0 08	0.14	0 58	0 22	0 39
	Max. precip.	0 51	1.02	1 16	1 27	1 40	1 55	1.63	1 66	1.71	1.79	1.93	2.51	2 73	3.12
	Duluth, Minn., July 21, 1909														
35	Obs. precip.	0.05	0 14	0 31	0 53	0 87	1 28	1 59	1 74	1.85	1 94	2 26	2.51	....	....
	Increment	0.05	0 09	0.17	0 22	0 34	0.41	0 31	0 15	0.11	0.09	0 32	0 25	....	....
	Max. precip.	0 41	0.75	1.06	1 28	1.45	1 60	1.71	1 80	1 96	2.12	2 26	2.51	....	....
	Duluth, Minn., Aug. 12, 1910														
36	Obs. precip.	0.16	0 62	1.14	1 38	1.40	....	.. .	..	....	....	....	...	...	....
	Increment	0.16	0.46	0 52	0.24	0.02	....	....	....	....	....	....	...	....	....
	Max. precip.	0 52	0 98	1.22	1.38	1.40	....	....	....	....	....	...		....	....

TABLE 12. — DATA FOR 100 TYPICAL INTENSE RAINSTORMS — 1896-1914 — (*Continued*)

No.	Station	Time in minutes													
		5	10	15	20	25	30	35	40	45	50	60	80	100	120
	Elkins, W. Va., Aug. 4, 1911														
37	Obs. precip.	0 34	0 70	0 94	1 36	1 72	1 95	2 11	2 22	2 28	2 32			.	.
	Increment .	0 34	0 36	0 24	0 42	0 36	0 23	0 16	0 11	0 06	0 04				..
	Max. precip.	0 42	0 78	1 02	1 38	1 72	1 95	2 11	2 22	2 28	2 32	.			..
	Escanaba, Mich., July 12, 1903														
38	Obs. precip. .	0 10	0 79	1 42	1 62	1 65	1 77	1 87	1 90						....
	Increment .	0 10	0 69	0 63	0 20	0 03	0 12	0 10	0 03						...
	Max. precip.	0 69	1 32	1 52	1 62	1 67	1 77	1 87	1 90						...
	Evansville, Ind., Aug. 10, 1908														
39	Obs. precip.	0 12	0 30	0 50	0 71	1 05	1 53	1 86	2 01	2 25	2 45	2 50			..
	Increment.	0 12	0 18	0 20	0 21	0 34	0 48	0 33	0 15	0 24	0 20	0 05			.
	Max. precip. .	0 48	0 82	1 15	1 36	1 56	1 75	1 95	2 15	2 33	2 45	2 50			....
	Ft. Worth, Texas, Sept. 21, 1900														
40	Obs. precip.	0 15	0 42	0 79	1 07	1 34	1 80	2 17	2 40	2 63	2 81	3 08	3 66	3 95	4.32
	Increment .	0 15	0 27	0 37	0 28	0 27	0 46	0 37	0 23	0 23	0 18	0 27	0 58	0 29	0 37
	Max. precip .	0 46	0 83	1 10	1 38	1 75	2 02	2 25	2 48	2 66	2 81	3 08	3 66	3 95	4.32
	Galveston, Texas, April 22, 1904														
	Obs. precip.	0 75	1 04	1 39	1 72	1 92	2 18	2 55	2 77	3 07	3 33	.	.		...
	Increment .	0 22	0 29	0 35	0 33	0 20	0 26	0 37	0 22	0 30	0 26		..	.	. .
	Max. precip.	0 51	0 94	1 38	1 88	2 28	2 67	2 94	3 27	3 54	3 87	.	...	..	...
	Cont. (50 min.+)														
41	Obs. precip.	3 59	3 99	4 50	4 93	5 37	5 87	6 26	6 53	6 86	7 13	.	..		...
	Increment . ..	0 26	0 40	0 51	0 43	0 44	0 50	0 39	0 27	0 33	0 27		..	..	...
	Max. precip.	4 15	4 41	4 67	4 97	5 19	5 56	5 82	6 03	6 35	6 70		.	.	..
	Cont. (100 min.+)														
	Obs. precip. .	7 46	7 74	7 95	8 11	8 26	8 36						.	..	..
	Increment .	0 33	0 28	0 21	0 16	0 15	0 10						..	.	...
	Max. precip.	6 99	7 21	7 42	7 58	7 73	7 83								...
	Galveston, Texas, Oct. 6, 1910														
42	Obs. precip.	0 17	0 36	0 58	0 94	1 22	1 47	1 74	1 83	1 89	2 09	2 27	4 07	5 99	6 28
	Increment	0 17	0 19	0 22	0 36	0 28	0 25	0 27	0 09	0 06	0 20	0 18	1 80	1 92	0 29
	Max. precip. . .	0 48	0 96	1 44	1 92	2 37	2 82	3 27	3 72	3 81	3 90	4 16	5.05	5 99	6 28
	Galveston, Texas, Oct. 22, 1913														
43	Obs. precip. ..	0 38	1 03	1 57	1 92	2 17	2 60	3 04	3 63	4 07	4 62	5 31	6 02	6 52	....
	Increment.... ...	0 38	0 65	0 54	0 35	0 25	0 43	0 44	0 59	0 44	0 55	0 69	0.71	0 50	...
	Max. precip.	0 65	1 19	1 58	2 02	2 45	2 80	3 14	4 69	4 24	4 62	5 31	6 02	6 52	....
	Grand Rapids, Mich., June 26, 1909														
44	Obs. precip.	0 36	0 84	1 10	1 31	1 51	1 71	1 86	2 01	2 11	2 19	...	...	....	....
	Increment.	0 36	0 48	0 26	0 21	0.20	0 20	0 15	0 15	0 10	0 08	.	....	....	....
	Max. precip. .. .	0 48	0 84	1 10	1 31	1.51	1 71	1 86	2 01	2 11	2 19	..	....	....	....

TABLE 12. — DATA FOR 100 TYPICAL INTENSE RAINSTORMS — 1896–1914 — (*Continued*)

No.	Station	Time in minutes													
		5	10	15	20	25	30	35	40	45	50	60	80	100	120
	Green Bay, Wis.,														
	Aug. 9, 1906														
	Obs. precip.	0.23	0.60	0.92	1.29	1.59	1.81	2.03	2.08		.				..
45	Increment	0.23	0.37	0.32	0.37	0.30	0.22	0.22	0.05				.	..	.
	Max. precip.	0.37	0.69	1.06	1.36	1.59	1.81	2.03	2.08		.	..	.	..	.
	Hannibal, Mo.,														
	July 29, 1910														
	Obs. precip.	0.32	0.67	0.84	0.86	0.89	0.93	0.95	1.19	1.54	1.79	2.07	2.65	3.27	3.87
46	Increment	0.32	0.35	0.17	0.02	0.03	0.04	0.02	0.24	0.35	0.25	0.28	0.58	0.62	0.60
	Max. precip.	0.35	0.67	0.84	0.98	1.12	1.26	1.41	1.55	1.70	1.86	2.17	2.77	3.27	3.87
	Houghton, Mich.,														
	Sept. 7, 1913														
	Obs. precip.	0.21	0.44	0.53	0.68	0.84	1.11	1.38	1.68	1.93	2.10	..	.	..	...
47	Increment	0.21	0.23	0.09	0.15	0.16	0.27	0.27	0.30	0.25	0.17	.		.	..
	Max. precip	0.31	0.57	0.84	1.09	1.26	1.42	1.68	1.87	2.10	2.26	...	.	..	..
	Cont. (50 min.+)														
	Obs. precip.	2.21	2.52	2.71	2.94	3.04	3.29	3.39	3.49	3.65	3.80		...	..	...
	Increment	0.11	0.31	0.19	0.23	0.10	0.25	0.10	0.10	0.16	0.15			...	...
	Max. precip.	2.45	2.61	2.76	2.86	3.08	3.29	3.38	3.49	3.65	3.80	..	..	...	...
	Cont. (100 min.+)														
	Obs. precip.	3.95	4.08	4.16	4.28	..	...	..	...	...	...	...	..	...	...
	Increment	0.15	0.13	0.08	0.12	...	..	.	..	.	..	..	..	..	...
	Max. precip.	3.95	4.08	4.16	4.28	.		.	...	..	..	..		...	...
	Indianapolis, Ind.,														
	Aug. 13, 1913														
48	Obs. precip.	0.24	0.50	0.95	1.46	1.78	1.98	2.05	2.18	2.41	2.56	2.66	2.80	.	...
	Increment	0.24	0.26	0.45	0.51	0.32	0.20	0.07	0.13	0.23	0.15	0.10	0.14	..	...
	Max. precip.	0.51	0.96	1.28	1.54	1.78	1.98	2.05	2.18	2.41	2.56	2.66	2.80	..	...
	Indianapolis, Ind.,														
	Sept. 30, 1902														
49	Obs. precip.	0.39	1.08	1.09	1.10	..	...	.		.	.	...	..	..	...
	Increment	0.39	0.69	0.01	0.01	...	...	..	...	...	..	.	..	...	...
	Max. precip.	0.69	1.08	1.09	1.10	...	..	..		...	.	...	...	...	...
	Jacksonville, Fla.,														
	Aug. 16, 1901														
50	Obs. precip.	0.11	0.83	1.00	1.08	1.22	1.28	...	...	..	..	...	...	...	...
	Increment	0.11	0.72	0.17	0.08	0.14	0.06	..	...	...	..	...	...	...	...
	Max. precip.	0.72	0.89	1.00	1.11	1.22	1.28	...	...	...	...	...	...	...	...
	Jacksonville, Fla.,														
	Sept. 6, 1907														
51	Obs. precip.	0.36	0.66	1.18	1.65	2.08	2.29	2.49	2.73	2.85	2.93	...	...	...	...
	Increment	0.36	0.30	0.52	0.47	0.43	0.21	0.20	0.24	0.12	0.08	...	...	...	...
	Max. precip.	0.52	0.99	1.42	1.72	2.08	2.29	2.49	2.73	2.85	2.93	...	...	...	...
	Jupiter, Fla.,														
	Oct. 28, 1908														
52	Obs. precip.	0.31	0.62	0.88	1.35	1.63	2.10	2.64	3.17	3.40	3.66	3.83	4.15	4.41	4.59
	Increment	0.31	0.31	0.26	0.47	0.28	0.47	0.54	0.53	0.23	0.26	0.17	0.32	0.26	0.18
	Max. precip.	0.54	1.07	1.54	1.82	2.29	2.55	2.86	3.17	3.40	3.66	3.83	4.15	4.41	4.59

TABLE 12. — DATA FOR 100 TYPICAL INTENSE RAINSTORMS — 1896-1914 — (*Continued*)

No.	Station	Time in minutes													
		5	10	15	20	25	30	35	40	45	50	60	80	100	120
	Kansas City, Mo., May 31, 1896														
53	Obs. precip.	0 80	1 05	....								.	.	..	....
	Increment	0 80	0 25	. .				..	.			..	.	...	....
	Max. precip.	0 80	1 05	.	..	.		.				..		..	...
	Kansas City, Mo., Aug. 23, 1906														
54	Obs. precip.	0 22	0 60	1 02	1 52	2 02	2 57	3 14	3 67	4 01	4 32	4 74	5 45	5 74	....
	Increment	0 22	0 38	0 42	0 50	0 50	0 55	0 57	0 53	0 34	0 31	0 42	0 71	0 29	...
	Max. precip.	0 57	1 12	1 65	2 15	2.65	3 07	3 45	3.79	4 10	4 32	4 74	5 45	5 74	....
	Kansas City, Mo., Sept. 15, 1914														
55	Obs. precip.	0 19	0 35	0 47	0 68	0 91	1 19	1.74	2 28	2 76	2 90	2 93	3 41	3 51	....
	Increment	0 19	0 16	0 12	0 21	0 23	0 28	0 55	0 54	0 48	0 14	0 03	0 48	0 10	....
	Max. precip.	0 55	1 09	1 57	1 85	2 08	2 29	2 43	2.57	2 76	2 90	2 93	3 41	3 51	....
	Knoxville, Tenn., Aug. 4, 1905														
56	Obs. precip.	0 08	0 13	0 23	0.29	0 41	0 83	1 29	1 65	1 89	1 99	.	..	....	....
	Increment	0 08	0 05	0 10	0 06	0 12	0 42	0 46	0 36	0 24	0 10	..	...	...	....
	Max. precip.	0 46	0 88	1 24	1 48	1 60	1 70	1 76	1 86	1 91	1 99	...	....	.. .	....
	Lincoln, Neb., May 27, 1914														
57	Obs. precip.	0 28	0 72	0 96	1 31	1 53	1 89	2 07	2 39	2 47	2 72	...	....	..	....
	Increment	0 28	0 44	0 24	0 35	0 22	0 36	0 18	0 32	0 08	0 25	....	.. .	...	....
	Max. precip.	0 44	0 72	1 03	1 31	1 61	1 89	2 11	2 39	2 47	2.72	...	....	....	...
	Lincoln, Neb., June 5, 1914														
	Obs. precip.	0 05	0 14	0 35	0 65	0.94	1 29	1 58	1 81	1 93	2 07	.	....	...	....
	Increment	0 05	0 09	0 21	0 30	0 29	0 35	0 29	0 23	0 12	0 14	..	..	....	...
	Max. precip.	0 35	0 64	0 94	1 23	1 46	1 67	1 79	1 93	2 06	2 18	..	....	...	....
	Cont. (50 min.+)														
58	Obs. precip.	2 20	2 32	2 57	2.80	2 90	2 92	2 92	2 93	2 93	2 93	. ..	...	....	....
	Increment	0.13	0 12	0 25	0 23	0 10	0 02	0 00	0.01	0 00	0 00	.	....	...	....
	Max. precip.	2 43	2 66	2 76	2 85	2 90	2 92	2 92	2 93	2 93	2 93	...	....	...	....
	Cont. (100 min.+)														
	Obs. precip.	3 03	3 26	3 35	3 40	3 57	3 61	...	....	.	...	. .	....	...	....
	Increment	0 10	0 23	0.09	0.05	0 17	0 04	.. .	...	...	...	....	...	...	....
	Max. precip.	3.03	3 26	3.35	3.40	3 57	3.61	.. .	..	....	..	.. .	....	....	....
	Lincoln, Neb., July 25, 1914														
59	Obs. precip.	0 29	0 72	1.26	1 88	2 18	2 53	2.78	2.90	2.99	3 06	....	....	....	....
	Increment	0.29	0 43	0 54	0.62	0.30	0.35	0.25	0.12	0 09	0 07	....	....	....	....
	Max. precip.	0 62	1.16	1.59	1.89	2 24	2.53	2.78	2.90	2.99	3.06	....	....	....	....
	Lynchburg, Va., June 24, 1905														
60	Obs. precip.	0.19	0 58	1 14	1 61	1.85	2.04	2 19	2.25	2.31	....	....	....	....	....
	Increment	0.19	0 39	0.56	0 47	0.24	0.19	0 15	0.06	0 06	...	....	....	....	....
	Max. precip.	0.56	1 03	1.42	1.66	1 85	2 04	2.19	2 25	2.31	....	....	....	....	....

TABLE 12. — DATA FOR 100 TYPICAL INTENSE RAIN-STORMS — 1896–1914 — (*Continued*)

No.	Station	Time in minutes													
		5	10	15	20	25	30	35	40	45	50	60	80	100	120
	Lynchburg, Va., Sept. 3, 1907														
61	Obs. precip.	0 25	0 34	0 56	0 94	1 30	1 61	1 88	2 02	2 27	2 69	3 49	. . .	.	.
	Increment	0 25	0 09	0 22	0 38	0 36	0 31	0 27	0 14	0 25	0 42	0 80	.	..	..
	Max. precip.	0 42	0 82	1 22	1 47	1 61	1 88	2 19	2.55	2 93	3 15	3 49	.		...
	Madison, Wis., Aug. 8, 1906														
62	Obs. precip.	0.21	0 74	1 29	1 58	1 82	2 09	2 29	2.50	2 85	3 19	3 61	4 54	4 84	...
	Increment	0 21	0 53	0 55	0 29	0 24	0 27	0 20	0 21	0 35	0.34	0.42	0 93	0 30	..
	Max. precip.	0 55	1 08	1 37	1 61	1 88	2 09	2 29	2.50	2.85	3.19	3 61	4 54	4 84	....
	Marquette, Mich., June 23, 1907														
63	Obs precip.	0 29	0 53	0 59	0 75	1 02	1 35	1 70	1 91	2 17	2.42	2 93	3 54	....	...
	Increment	0 29	0 24	0 06	0 16	0 27	0 33	0 35	0 21	0 26	0.25	0 51	0 61	. .	....
	Max. precip.	0 35	0 68	0 95	1.16	1 42	1 67	1.92	2 18	2.34	2.49	2.93	3 54	....	....
	Memphis, Tenn., March 9, 1901														
64	Obs. precip.	0.78	0 92	0 97	1.02	1.05	..	. .	...	...	...	....	....	....	. .
	Increment	0 78	0 14	0 05	0.05	0 03	....	. .	....	...	....	....	....	.	. .
	Max. precip.	0.78	0.92	0.97	1.02	1.05	....	...	....	...	...	....	....	...	. .
	Meridian, Miss., Aug. 13, 1906														
65	Obs. precip.	0 17	0.38	0 76	1 25	1.81	2 28	2 53	2 73	2.89	3 06	3 63	3 74	.. .	....
	Increment	0 17	0.21	0 38	0 49	0.56	0 47	0.25	0 20	0 16	0 17	0 57	0 11	..	....
	Max. precip.	0 56	1.05	1.52	1 90	2.15	2 36	2 56	2 73	2 89	3 06	3 63	3 74	....	....
	Miami, Fla., Nov. 8, 1914														
66	Obs. precip.	0.10	0 46	0 83	1.16	1.47	1.77	2 04	2 23	2 36	2 56	2 96	3 48	3 90	4.59
	Increment	0 10	0.36	0.37	0 33	0 31	0 30	0.27	0 19	0.13	0 20	0 40	0 52	0.42	0 69
	Max. precip.	0.37	0.73	1.06	1.37	1.67	1.94	2.13	2 26	2 46	2.66	2.99	3.49	3.97	4.59
	Minneapolis, Minn., Aug. 22, 1914														
67	Obs. precip.	0 30	0 57	0 83	1 03	1.40	1.93	2 15	2 21	....	....	....	...	....	...
	Increment	0 30	0 27	0.26	0 20	0 37	0.53	0.22	0.06	.. .	....	....	...	....	....
	Max. precip.	0.53	0.90	1.12	1.36	1.63	1.93	2.15	2.21	....	....	....	....	....	....
	Montgomery, Ala., May 30, 1905														
68	Obs. precip.	0.08	0.17	0.36	0.70	1.08	1.44	1.98	2 48	2.85	3.03	3 46	...	....	....
	Increment	0.08	0.09	0.19	0 34	0.38	0 36	0.54	0 50	0 37	0.18	0.43	....	....	...
	Max. precip.	0.54	1.04	1.41	1.78	2.15	2 49	2.68	2.88	3.10	3.29	3.46	....	....	....
	Moorhead, Minn., Aug. 29, 1908														
69	Obs. precip.	0.34	1.02	1.24	1.28	1.33	1.34	1.35	1.38	1.40	1.40	1.72	1.98	....	....
	Increment	0.34	0.68	0.22	0.04	0.05	0.01	0.01	0.03	0.02	0.00	0.32	0.26	....	....
	Max. precip.	0.68	1.02	1.24	1.28	1.33	1.34	1.35	1.38	1.40	1.40	1.72	1.98	....	....

TABLE 12. — DATA FOR 100 TYPICAL INTENSE RAINSTORMS — 1896–1914 — (*Continued*)

No	Station	Time in minutes													
		5	10	15	20	25	30	35	40	45	50	60	80	100	120
	New Orleans, La , Sept. 30, 1905														
70	Obs. precip..	0 29	0 78	1 38	1 97	2 23	2 37	2 45							..
	Increment	0 29	0 49	0 60	0 59	0 26	0 14	0 08		.					...
	Max. precip.........	0 60	1 19	1 68	1 97	2 23	2 37	2 45		.					...
	New York City, N. Y., July 10, 1905														
71	Obs. precip.	0 43	0 95	1 63	1 88	1 99	2 08	2 11	..						.
	Increment	0 43	0 52	0 68	0 25	0 11	0 09	0 03	.		.	.			.
	Max. precip..	0 68	1 20	1 63	1 88	1 99	2 08	2 11	.		.	.			...
	New York City (Borough of Richmond) Oct. 1, 1913														
72	Obs. precip.		0 20	.	0 48	..	1 00		1 75		2 60	3 30	4 70	5 65	6 20
	Increment..		0 20		0 28		0 52	.	0 75		0 85	0 70	0 55	0 45	0 40
	Max. precip.........		0 85	.	1 60	..	2 40	.	3 15	..	3 70	4 22	5 17	5 72	6 20
	Norfolk, Va., Aug. 14, 1898														
73	Obs. precip..	0 22	0 45	0 67	1 03	1 34	1 56	1 72	1 84	2 04	2 14	2 69	2 59	4 44	4 73
	Increment	0 22	0 23	0 22	0 36	0 31	0 22	0 16	0 12	0 20	0 10	0 55	0 90	0 85	0 29
	Max. precip....	0 36	0 67	0 89	1 12	1.34	1 56	1 72	1 84	2 04	2 24	2 69	3 59	4 44	4 73
	Oklahoma, Okla., June 23, 1908														
74	Obs. precip.... ...	0 10	0 17	0 28	0 47	0 79	1 07	1 45	1 87	2 15	2 40	2 65	.		..
	Increment..... . . .	0 10	0 07	0 11	0 19	0 32	0 28	0 38	0 42	0 28	0 25	0 25	.		..
	Max. precip....... ...	0 42	0 80	1 08	1.40	1 68	1.93	2 12	2 25	2 37	2 48	2 65		.	..
	Pensacola, Fla., Sept. 29, 1906														
	Obs. precip..........	0 35	0 76	1 13	1 62	2 00	2 30	2 53	2 79	3 08	3 35	.			..
	Increment	0 35	0 41	0 37	0.49	0 38	0 30	0 23	0 26	0 29	0 27	..	..	.	...
	Max. precip. .	0 49	0 87	1 24	1.65	2 00	2 30	2 53	2 79	3 08	3 35	.	.		..
	Cont. (50 min.+)														
	Obs. precip....	3 57	3 82	4 02	4.16	4 28	4 41	4 67	4 89	5 08	5 33	...	..	.	. .
	Increment	0 22	0 25	0 20	0 14	0 12	0 13	0 26	0 22	0 19	0 25		.		. .
75	Max. precip.... . .	3 57	3 82	4.02	4.16	4 28	4 41	4 67	4 89	5.08	5 33	.	.	.	...
	Cont. (100 min.+)														
	Obs. precip..... . .	5 66	5 90	6 10	6.24	6 27	6 28	6 28	6 33	6 47	6 63	....	.	...	...
	Increment	0 33	0 24	0 20	0.14	0 03	0 01	0 00	0 05	0 14	0 16	..	..	. .	. . .
	Max. precip.	5.66	5.90	6 10	6 24	6 27	6 28	6 28	6.33	6.47	6 63	...	....	..	....
	Cont. (150 min.+)														
	Obs. precip... .	6 72	6 81	.	.	..	. .	..	...	....	....	....	..	...	...
	Increment....	0 09	0 09	...	...	. .	....	.	..	...		....	...	...	..
	Max. precip...........	6.72	6 81	..	....	....	...	..	....	...	....	....	....	....	...
	Pensacola, Fla., Oct. 20, 1909														
76	Obs. precip..........	0.05	0 12	0 26	0 33	0 92	1.72	2 45	3 21	3 70	3.98	4.27	4.49	4 73	4 82
	Increment...........	0 05	0.07	0 14	0.07	0.59	0 80	0 73	0 76	0 49	0 28	0 29	0 22	0.24	0 09
	Max. precip..........	0.80	1.53	2.29	2 88	3.37	3 65	3 79	3 94	4 01	4.15	4.27	4.49	4.73	4.82

TABLE 12. — DATA FOR 100 TYPICAL INTENSE RAINSTORMS — 1896–1914 — (*Continued*)

No	Station	Time in minutes													
		5	10	15	20	25	30	35	40	45	50	60	80	100	120
	Philadelphia, Pa., Aug. 6, 1905														
77	Obs. precip. .	0 11	0 29	0 55	0 96	1 45	1 90	2 10	2 19	2 32			.	.	.
	Increment . . .	0 11	0 18	0 26	0 41	0 49	0 45	0 20	0 09	0 13				.	.
	Max. precip.	0 49	0 94	1 35	1 61	1 81	1 97	2 10	2 19	2 32		.			. .
	Raleigh, N C., July 14, 1914														
78	Obs precip. .	0 22	0 56	0 86	1 48	2 21	2 57	2 76	2 87	2 94	2 99	.	.		. .
	Increment .	0 22	0 34	0 30	0 62	0 73	0 36	0 19	0 11	0 07	0 05				. .
	Max. precip. . .	0 73	1 35	1 71	2 01	2 35	2 57	2 76	2 87	2 94	2 99	.			. . .
	Richmond, Va., Aug. 19, 1908														
79	Obs. precip. .	0 40	0 86	1 14	1 57	2 27	2 60	2 69	2 75	2 85	2 91	.		.	. .
	Increment . . .	0 40	0 46	0 28	0 43	0 70	0 33	0 09	0 06	0 10	0 06	.	.	. .	. .
	Max. precip.. . .	0 70	1 13	1 46	1 87	2 27	2 60	2 69	2 75	2 85	2 91			.	...
	Rochester, N. Y., July 11, 1897														
80	Obs. precip....... ..	0 14	0 44	0 71	1 06	1 36	1 70	1 84	1 96	2 12	2 24	2 49	2 74	.	....
	Increment........ . .	0 14	0 30	0 27	0 35	0 30	0 34	0 14	0 12	0 16	0 12	0 25	0 25	.	....
	Max. precip....... .	0.35	0 65	0 99	1 26	1 56	1 70	1 84	1.98	2 12	2 24	2 49	2 74	..	....
	St. Louis, Mo., March 4, 1897														
81	Obs. precip...... ...	0 88	0 93	0 98	0 99	1 00	1 03	1 05	1 06	1 09	1 14	1 23	1 36	.	...
	Increment...	0 88	0 05	0 05	0 01	0 01	0 03	0 02	0 01	0 03	0 05	0 09	0 13	..	...
	Max. precip....	0 88	0 93	0 98	0 99	1 00	1 03	1 05	1 06	1 09	1 14	1 23	1 36	.	...
	St. Louis, Mo., May 1, 1898														
82	Obs. precip...........	0.27	0 43	0 48	1 22	1 23	1.24	..	....	..	...	..	...	.	.. .
	Increment	0 27	0 16	0 05	0 74	0 01	0 01	...	. .	. .	...	. .	...	....	....
	Max. precip....	0.74	0 79	0 95	1 22	1 23	1 24	..	.	....	.	....	...	....	....
	St. Louis, Mo., July 14, 1912														
83	Obs. precip...........	0 14	0 41	0 72	0 99	1 18	1 30	1 58	1 98	2 28	2 50	2 95	3.07	....	....
	Increment...	0 14	0 27	0 31	0 27	0 19	0 12	0 28	0 40	0 30	0 22	0 45	0.12	....	....
	Max. precip...........	0.40	0.70	0 98	1.20	1 43	1.65	1.87	2 14	2 36	2 58	2 95	2.07	....	....
	St. Paul, Minn., Aug. 9, 1902														
84	Obs. precip..........	0 06	0 12	0 33	0 71	1 12	1.57	2 02	2 18	2 27	2 38	2 51	2 69	2 93	3 04
	Increment	0.06	0 06	0 21	0 38	0.41	0.45	0.45	0 16	0 09	0 11	0 13	0 18	0 24	0 11
	Max. precip...........	0.45	0.90	1 31	1.69	1.90	2 06	2.15	2 26	2.32	2.39	2.51	2.69	2.93	3 04
	Sandusky, Ohio, Aug. 7, 1906														
85	Obs. precip..	0 26	0 49	0 78	1.34	1 59	1.74	1 98	2 11	2.16	2 22	....	...	....	....
	Increment............	0 26	0.23	0.29	0.56	0.25	0.15	0 24	0 13	0 05	0.06	...	....	....	....
	Max. precip.....	0 56	0 85	1 10	1.33	1 59	1 74	1 98	2 11	2 16	2 22	..	...	....	....

TABLE 12. — DATA FOR 100 TYPICAL INTENSE RAINSTORMS — 1896–1914 — (*Continued*)

No.	Station	Time in minutes													
		5	10	15	20	25	30	35	40	45	50	60	80	100	120
	Shreveport, La.,														
	July 23, 1905														
	Obs. precip.	0 12	0 30	0 42	0 72	0 97	1 31	1 62	1 95	2 22	2 49	.	..	...	...
	Increment.	0.12	0 18	0 12	0 30	0 25	0 34	0 31	0 33	0 27	0 27		....	...	....
	Max. precip.	0 34	0 65	0 98	1 25	1 53	1 84	2 09	2 39	2 57	2 69	. .	...	....	...
	Cont. (50 min.+)														
	Obs. precip.	2 81	2 99	3 08	3 15	3 25	3 35	3 50	3 75	3 92	4 12		..	....	..
	Increment	0 32	0 18	0 09	0 07	0 10	0 10	0 15	0 25	0 17	0 20			...	...
86	Max. precip.	2 87	2 99	3 08	3 15	3 25	3 25	3 50	3 75	3 92	4 12		..	..	..
	Cont. (100+)														
	Obs. precip.	4 30	4 52	4 68	5 00	5 31	5 48	5 55	5 67	5 90	6 06		.		..
	Increment	0 18	0 22	0 16	0 32	0 31	0 17	0 07	0 12	0 23	0 16		.		...
	Max. precip.	4 30	4 52	4 68	5 00	5 31	5 48	5 55	5 67	5 90	6 06		...		...
	Cont. (150 min.+)														
	Obs. precip.	6 20	6 28	6 32	6 36	6 43	6 49		.	.			..	.	..
	Increment	0 14	0 08	0 04	0 04	0 07	0 06	..	...	. .	.	..	...		...
	Max. precip.	6 20	6 28	6 32	6 36	6 43	6 49	..	.	..	...		..	. .	..
	Springfield, Ill.,														
	July 6, 1912														
87	Obs. precip.	0 38	0 80	1 20	1 43	1 73	2 10	2 31	2 42	2 56	2 70	2 75	...	.	...
	Increment.	0 38	0 42	0 40	0 23	0 30	0 37	0 21	0 11	0.14	0 14	0 05	...	.	....
	Max. precip.	0 42	0 82	1 20	1.43	1 73	2 10	2 31	2 42	2.56	2.70	2 75	...	.	...
	Tampa, Fla.,														
	June 20, 1905														
88	Obs. precip.	0 12	0 17	0 45	0 62	0 90	1 32	1 71	2 30	2 57	3 00	3 13	3 37	3.49	...
	Increment	0 12	0 05	0 28	0 17	0 28	0 42	0 39	0 59	0 27	0 43	0 13	0 24	0 12	....
	Max. precip.	0 59	0 98	1 40	1 68	2 10	2 38	2 55	2 83	2 88	3 00	3 13	3 37	3.49	...
	Taylor, Texas,														
	Apr. 29, 1905														
89	Obs. precip.	0 45	1 35	2 25	2 75	2 83	2 89	.	.	.	..	...	...		..
	Increment	0 45	0 90	0 90	0 50	0 08	0 06		.		..	...	....		..
	Max. precip.	0 90	1 80	2 30	2 75	2 83	2 89	.	..		..	. .	...	..	. ..
	Taylor, Texas,														
	June 25, 1906														
90	Obs. precip.	0 26	0 70	1 12	1 42	1 65	1 87	2 19	2 55	2 89	3 15	3 40	3 80	4 03	. ..
	Increment	0 26	0 44	0 42	0 30	0 23	0.22	0 32	0 36	0 34	0 26	0 25	0 40	0 23	...
	Max. precip.	0 44	0 86	1 16	1 42	1 65	1 87	2 19	2 55	2.89	3 15	3 40	3 80	4.03	...
	Thomasville, Ga.,														
	June 27, 1909														
91	Obs. precip.	0 21	0.52	0 64	0 78	1 11	1 68	2 23	2 94	3 38	3 77	4.14	4 26		....
	Increment	0 21	0 31	0 12	0 14	0 33	0 57	0 55	0.71	0 44	0 39	0.37	0 12		..
	Max. precip.	0 71	1.26	1 83	2.27	2 66	2 99	3 17	3 36	3 56	3 77	4 14	4 26		....
	Toledo, Ohio,														
	June 24, 1911														
92	Obs. precip.	0 37	0 79	0 88	1 27	1.62	1.88	2.00	2 04	2 13	....	...	.	. .	...
	Increment	0 37	0 42	0 09	0.39	0.35	0.26	0.12	0 04	0 09	.. .	..	.	...	....
	Max. precip.	0 42	0.79	1 00	1 27	1.62	1.88	2 00	2.04	3 13	...	...	....	....	....

TABLE 12. — DATA FOR 100 TYPICAL INTENSE RAIN-STORMS — 1896–1914 — (*Concluded*)

No.	Station	Time in minutes													
		5	10	15	20	25	30	35	40	45	50	60	80	100	120
	Topeka, Kan., Sept. 6, 1909														
93	Obs. precip....... .	0 09	0 36	0 62	0 73	0 92	1 10	1 36	1 48	1 67	1 85	2 14	2 71	3 20	...
	Increment	0 09	0 27	0 26	0 11	0 19	0 18	0 26	0 12	0 19	0 18	0 29	0 57	0 49	.
	Max. precip..... ...	0 27	0 53	0 64	0 83	1 01	1 27	1 39	1 58	1 76	1 90	2 19	2 74	3 20	.
	Valentine, Neb., Aug. 12, 1909														
94	Obs. precip...	0 17	0 34	0 47	0 65	0 79	1 19	1 58	2 02	2 39	2 64	3 01	2 21	.	....
	Increment . .	0 17	0 17	0 13	0 18	0 14	0 40	0 39	0 44	0 37	0 25	0 37	0 20		...
	Max. precip.... ..	0 44	0 83	1.23	1 60	1 85	2 04	2 22	2 36	2 54	2 67	3 01	3 21	.	...
	Washington, D. C., Aug. 10, 1897														
95	Obs. precip. .. .	0 18	0 56	1 08	1 62	1 86	1 87	1 88	1 90	1 92		..	.	.	..
	Increment . ..	0 18	0 38	0 52	0 54	0 24	0 01	0 01	0 02	0 02	.	...	..		...
	Max. precip....... ..	0 54	1 06	1 44	1 68	1 86	1 87	1 88	1.90	1 92		..	. .		...
	Washington, D. C., July 5, 1905														
96	Obs. precip...... ...	0 30	0 54	0.75	0 93	1 11	1 42	1 74	1 83	1 99	2 25	2 72	3 23		. .
	Increment..	0 30	0 24	0 21	0 18	0 18	0 31	0 32	0 09	0 16	0 26	0 47	0 51		...
	Max. precip...... . .	0 32	0 63	0 81	0 99	1 20	1 44	1.74	1 83	1 99	2 25	2 72	3 23	..	....
	Washington, D. C., July 30, 1913														
97	Obs. precip..	0 52	1 21	1 51	1 56	....	....	...	. .	...	...	....	...	. .	...
	Increment	0.52	0 69	0.30	0 05	....	....	...	....	...	..	. .	...	. .	...
	Max. precip......... .	0 69	1.21	1 51	1.56	.	....	....	. .	...	....	....	...	....	....
	Wichita, Kan., Sept. 17, 1905														
98	Obs. precip.	0 23	0 36	0 41	0 82	1 32	1 66	1 84	1 97	2.17	2 59	....	....	..	...
	Increment...	0 23	0.13	0 05	0 41	0 50	0 34	0.18	0 13	0 20	0 42	....	..	....	....
	Max. precip....	0 50	0.91	1 25	1 43	1 56	1.77	2.18	2 23	2 36	2.59	...	..	....	....
	Wytheville, Va., July 21, 1908														
99	Obs. precip........	0.24	0 68	1 17	1 59	1.79	2.10	2 22	2 32	....	....	....	..	...	....
	Increment..........	0.24	0 44	0 49	0.42	0 20	0.31	0 12	0.10	..	....	....	...	....	....
	Max. precip.........	0.49	0 93	1 35	1 59	1.79	2 10	2.22	2.32	....	....	....	..	...	. .
	Yankton, S. D., May 26, 1912														
100	Obs. precip.	0 22	0.72	1.12	1 49	1 67	1.71	1 77	...	....	...	....	....	....	....
	Increment...........	0 22	0 50	0.40	0 37	0 18	0 04	0 06	...	....	...	....	....	....	....
	Max. precip.	0 50	0.90	1.27	1 49	1 67	1.71	1 77	....	....	....	....	....	....	....

TABLE 13.—MOST EXCEPTIONAL RATE OF PRECIPITATION DURING ONE HUNDRED INTENSE RAINSTORMS—1896–1914 *

No.	Station	Date	Precipitation	
			Amount, inches	Time, minutes
1	Augusta, Ga.	June 18, 1911	1.24	5
2	St. Louis, Mo.	March 4, 1897	0.88	5
3	Denver, Colo.	July 14, 1912	0.87	5
4	Atlantic City, N. J.	May 31, 1906	0.83	5
5	Kansas City, Mo.	May 31, 1896	0.80	5
6	Buffalo, N. Y.	March 20, 1897	0.79	5
7	Cleveland, Ohio	Aug. 29, 1903	0.78	5
8	Memphis, Tenn.	March 9, 1901	0.78	5
9	St. Louis, Mo.	May 1, 1898	0.74	5
10	Jacksonville, Fla.	Aug. 16, 1901	0.72	5
11	Asheville, N. C.	June 12, 1914	0.70	5
12	Indianapolis, Ind.	Sept. 30, 1902	0.69	5
13	Moorhead, Minn.	Aug. 29, 1908	0.68	5
14	Dallas, Texas	Sept. 22, 1914	0.62	5
15	Taylor, Texas	April 29, 1905	1.80	10
16	Raleigh, N. C.	July 14, 1914	1.35	10
17	Washington, D. C.	July 30, 1913	1.21	10
18	Bentonville, Ark.	April 23, 1908	1.19	10
19	Cleveland, Ohio	Aug. 20, 1901	1.09	10
20	Dodge City, Kansas	July 17, 1911	1.02	10
21	Duluth, Minn.	Aug. 12, 1910	0.98	10
22	Pensacola, Fla.	Oct. 20, 1909	2.29	15
23	Thomasville, Ga.	June 27, 1909	1.83	15
24	Anniston, Ala.	Sept. 5, 1906	1.81	15
25	New Orleans, La.	Sept. 30, 1905	1.68	15
26	New York City, N. Y.	July 10, 1905	1.63	15
27	Kansas City, Mo.	Sept. 15, 1914	1.57	15
28	Escanaba, Mich.	July 12, 1903	1.52	15
29	Lynchburg, Va.	June 24, 1905	1.42	15
30	Davenport, Iowa	July 14, 1910	1.38	15
31	Philadelphia, Pa.	Aug. 6, 1905	1.35	15
32	Cairo, Ill.	July 30, 1913	1.32	15
33	Chattanooga, Tenn.	Aug. 22, 1912	1.26	15
34	Knoxville, Tenn.	Aug. 4, 1905	1.24	15
35	Baltimore, Md.	Aug. 25, 1911	2.03	20
36	Washington, D. C.	Aug. 10, 1897	1.68	20
37	Cincinnati, Ohio	May 20, 1902	2.13	25
38	Concordia, Kansas	Aug. 26, 1908	1.99	25
39	Yankton, S. D.	May 26, 1912	1.67	25
40	Richmond, Va.	Aug. 19, 1908	2.60	30
41	Wytheville, Va.	July 21, 1908	2.10	30
42	St. Paul, Minn.	Aug. 9, 1902	2.06	30
43	Toledo, Ohio	June 24, 1911	1.88	30
44	Birmingham, Ala.	July 24, 1910	1.87	30
45	Lincoln, Neb.	July 25, 1914	2.78	35
46	Concord, N. H.	July 7, 1907	2.60	35
47	Minneapolis, Minn.	Aug. 22, 1914	2.15	35
48	Chatanooga, Tenn.	Aug. 17, 1912	2.10	35
49	Green Bay, Wis.	Aug. 9, 1906	2.03	35
50	Grand Rapids, Mich.	June 26, 1909	1.86	35

* Rates *below the maximum for each time interval* were selected so as to secure representation of a large number of storms and different localities.

TABLE 13.—MOST EXCEPTIONAL RATE OF PRECIPITATION DURING ONE HUNDRED INTENSE RAINSTORMS—1896–1914—(*Concluded*)

No.	Station	Date	Precipitation	
			Amount, inches	Time, minutes
51	Atlanta, Ga.	Aug. 20, 1914	2 89	40
52	Tampa, Fla.	June 20, 1905	2 83	40
53	Bismarck, N. D.	Aug. 9, 1909	2 80	40
54	Jacksonville, Fla.	Sept. 6, 1907	2 73	40
55	Elkins, W. Va.	Aug. 4, 1911	2.22	40
56	Sandusky, Ohio	Aug. 7, 1906	2 11	40
57	Asheville, N. C	Aug. 12, 1911	2 65	45
58	Indianapolis, Ind.	Aug. 13, 1913	2.41	45
59	Evansville, Ind.	Aug. 10, 1908	2.33	45
60	Jupiter, Fla.	Oct. 28, 1908	3 66	50
61	Lincoln, Neb.	May 27, 1914	2 72	50
62	Springfield, Ill.	July 6, 1912	2 70	50
63	Wichita, Kansas.	Sept. 17, 1905	2 59	50
64	Meridian, Miss.	Aug. 13, 1906	3 63	60
65	Lynchburg, Va.	Sept. 3, 1907	3 49	60
66	Abilene, Texas.	July 31, 1911	3 46	60
67	Montgomery, Ala.	May 30, 1905	3 46	60
68	Cairo, Ill.	June 28, 1905	3 15	60
69	Valentine, Neb.	Aug. 12, 1909	3 01	60
70	St. Louis, Mo.	July 14, 1912	2.95	60
71	Columbia, Mo.	June 29, 1909	2 73	60
72	Oklahoma, Okla.	June 23, 1908	2 65	60
73	Kansas City, Mo.	Aug. 23, 1906	5 45	80
74	Marquette, Mich.	June 23, 1907	3.54	80
75	Washington, D. C.	July 5, 1905	3 23	80
76	Anniston, Ala.	April 22, 1909	2 84	80
77	Rochester, N. Y.	July 11, 1897	2.74	80
78	Duluth, Minn.	July 21, 1909	2 51	80
79	Galveston, Texas.	April 22, 1904	6.70	100
80	Dodge City, Kansas	Sept. 16, 1906	4 85	100
81	Madison, Wis.	Aug. 8, 1906	4 84	100
82	Taylor, Texas	June 25, 1906	4 03	100
83	Atlanta, Ga.	March 15, 1912	3 37	100
84	Des Moines, Iowa	July 15, 1907	3 29	100
85	Topeka, Kansas	Sept. 6, 1909	3 20	100
86	Pensacola, Fla.	Sept. 29, 1906	6 10	115
87	Lincoln. Neb.	June 5, 1914	3 35	115
88	Galveston, Texas	April 23, 1904	7.58	120
89	Galveston, Texas	Oct. 6, 1910	6.28	120
90	New York City, N. Y.	Oct. 1, 1913	6.20	120
91	Shreveport, La.	July 23, 1905	5 00	120
92	Norfolk, Va.	Aug. 14, 1898	4.73	120
93	Miami, Fla.	Nov. 8, 1914	4.59	120
94	Abilene, Texas	May 22, 1908	4.42	120
95	Atlanta, Ga.	July 23, 1898	4.32	120
96	Fort Worth, Texas	Sept. 21, 1900	4.32	120
97	Houghton, Mich.	Sept. 7, 1913	4.28	120
98	Abilene, Texas	Oct. 22, 1908	3.94	120
99	Hannibal. Mo.	July 29, 1910	3.87	120
100	Del Rio, Texas	July 2, 1914	3.56	120

TABLE 13.—MOST EXCEPTIONAL RATE OF PRECIPITATION DURING THIRTY-SEVEN EARLIER RAINSTORMS *

No.	Station	Date	Precipitation	
			Amount, inches	Time, minutes
1	Ft. McPherson, Neb.	May 27, 1868	1 50	5
2	Kirkwood, S. C.	Sept. 14, 1890	1.50	10
3	Huron, S. D.	July 26, 1885	1.30	10
4	Albany, N. Y.	July 10, 1876	1 22	10
5	Alpena, Mich.	Sept. 20, 1884	1.05	11
6	Galveston, Texas	June 4, 1871	3 95	14
7	Embarrass, Wis.	May 28, 1881	2 30	15
8	Sandusky, Ohio	July 11, 1879	2.25	15
9	Amano, Va.	July 31, 1878	1.56	15
10	Ft. Randall, S. D.	May 28, 1873	1.56	15
11	Havre, Tenn.	Sept. 10, 1889	3 00	20
12	Jupiter, Fla.	Aug. 21, 1893	2 12	20
13	West Leavenworth, Kan.	July 21, 1887	1 90	20
14	Fort Scott, Kan.	Oct. 2, 1881	1.80	20
15	Sheldon, Minn.	June 23, 1890	2 07	25
16	Biscayne, Fla.	March 28, 1874	4 10	30
17	Logansport, Md.	July 7, 1879	3 50	30
18	Colorado Springs, Colo.	Aug. 14, 1890	2 75	30
19	College Hill, Ohio	May 27, 1888	2 38	30
20	Providence, R. I.	Aug. 6, 1878	3 50	35
21	Newton, Penn.	Aug. 5, 1843	5.50	40
22	Jacksonville, Fla.	July 6, 1886	3.49	40
23	Black Rock, Ark.	April 20, 1892	3.42	40
24	East Peoria, Ill.	June 13, 1893	2.65	40
25	Monroe, La.	Sept. 22, 1890	4.12	45
26	Dodge City, Kan.	June 19, 1888	3 24	45
27	Alexandria, S. D.	May 21, 1893	3.15	45
28	Jupiter, Fla.	Nov. 4, 1893	3.50	51
29	Tridelphia, W. Va.	July 19, 1888	6 90	55
30	St. Louis, Mo.	Aug. 15, 1848	5 05	60
31	Cumberland, Md.	June 4, 1892	4.64	60
32	Atwood, Ill.	June 12, 1890	4 36	60
33	Galveston, Texas	Feb. 22, 1888	3 31	60
34	Spooner, Wis.	June 23, 1894	3.00	60
35	Rock Island, Ill.	July 13, 1889	5.16	75
36	Plover, Wis.	Aug. 3, 1890	4.50	90
37	Brandywine, Pa.	Aug. 5, 1843	10 00	120

* These data were collected from various publications and are not considered entirely reliable

TABLE 14. — INTENSE PRECIPITATION EXCEEDED WITH GIVEN FREQUENCY AS DETERMINED FROM RECORDS OF INDIVIDUAL STATIONS — 1896–1914 inclusive

Station	Precipitation exceeded once in													
	10 Years							5 Years						
	Time in minutes							Time in minutes						
	5	10	15	30	60	100	120	5	10	15	30	60	100	120
Group No. 1														
Galveston	0.66	1.05	1.47	2.40	3.40	4.00	4.50	0.57	0.98	1.36	2.20	3.00	3.25	3.75
New Orleans	0.58	1.12	1.50	2.00	2.60	3.35	3.50	0.56	1.05	1.34	1.90	2.50	3.00	3.00
Jacksonville	0.66	1.00	1.50	2.15	2.60	3.00	3.10	0.60	0.96	1.40	2.00	2.25	2.50	2.90
Average	0.63	1.06	1.49	2.18	2.87	3.45	3.70	0.58	1.00	1.37	2.03	2.58	2.92	3.22
	2 Years							1 Year						
Galveston	0.52	0.91	1.20	1.76	2.32	2.80	2.80	0.42	0.74	0.96	1.48	1.98	2.18	2.20
New Orleans	0.52	0.89	1.10	1.67	2.10	2.40	2.40	0.44	0.75	0.99	1.50	1.80	1.95	1.95
Jacksonville	0.53	0.89	1.15	1.50	1.95	2.25	2.30	0.47	0.79	1.02	1.30	1.60	1.80	1.85
Average	0.52	0.90	1.15	1.64	2.12	2.48	2.50	0.44	0.76	0.99	1.43	1.79	1.98	2.00
	10 Years							5 Years						
Group No. 2														
New York	0.53	0.90	1.20	1.60	2.00	2.40	2.60	0.43	0.75	0.95	1.20	1.70	2.10	2.15
Philadelphia	0.60	0.95	1.20	1.80	2.30	2.60	2.60	0.50	0.85	1.00	1.60	1.90	2.20	2.30
Washington	0.55	1.00	1.35	1.80	2.65	3.00	3.00	0.51	0.83	1.10	1.60	2.50	2.50	2.50
Norfolk	0.57	0.90	1.15	1.70	2.00	2.60	2.80	0.50	0.83	1.07	1.50	1.80	1.95	2.00
Raleigh	0.58	1.00	1.32	1.80	2.35	2.50	2.50	0.53	0.90	1.15	1.65	2.20	2.25	2.30
Savannah	0.58	1.00	1.20	1.75	2.20	2.55	2.60	0.50	0.85	1.05	1.58	2.00	2.40	2.45
Atlanta	0.55	0.90	1.20	1.80	2.30	2.60	2.60	0.50	0.78	1.00	1.65	2.00	2.25	2.35
Little Rock	0.50	0.85	1.05	1.65	2.40	2.60	2.80	0.44	0.75	0.90	1.55	2.20	2.40	2.50
Fort Worth	0.52	0.85	1.10	1.85	2.40	2.60	2.80	0.46	0.78	1.05	1.65	2.00	2.30	2.35
Abilene	0.55	0.90	1.20	2.00	3.00	3.50	3.75	0.48	0.78	1.10	1.60	2.40	2.60	2.80
Bentonville	0.60	0.90	1.20	1.60	2.00	2.40	2.60	0.55	0.80	1.00	1.40	1.80	2.00	2.20
St. Louis	0.65	0.90	1.10	1.50	2.00	2.20	2.40	0.55	0.80	1.00	1.35	1.60	1.80	1.85
Kansas City	0.58	1.00	1.20	1.60	2.20	2.60	2.60	0.53	0.90	1.00	1.50	2.00	2.35	2.35
Lincoln	0.55	1.00	1.20	1.70	2.20	2.60	2.80	0.47	0.80	1.00	1.40	2.00	2.30	2.40
Des Moines	0.55	0.90	1.20	1.60	2.00	2.40	2.60	0.48	0.84	1.10	1.40	1.60	2.00	2.10
Average	0.56	0.93	1.19	1.72	2.27	2.61	2.74	0.50	0.82	1.03	1.51	1.98	2.23	2.31

TABLE 14. — INTENSE PRECIPITATION EXCEEDED WITH GIVEN FREQUENCY AS DETERMINED FROM RECORDS OF INDIVIDUAL STATIONS — 1896–1914 inclusive — (*Continued*)

Station	Precipitation exceeded once in													
	2 Years							1 Year						
	Time in minutes							Time in minutes						
	5	10	15	30	60	100	120	5	10	15	30	60	100	120
Group No. 2														
New York	0.37	0.62	0.78	1.10	1.40	1 70	1.75	0.32	0 50	0 65	0.90	1 18	1 25	.....
Philadelphia	0.40	0.68	0.88	1.15	1.50	1.50	1.55	0 35	0 57	0 77	0 97	1.10	1 20	.....
Washington	0.44	0.70	0 90	1.45	1.70	1.88	1.88	0 38	0 65	0 80	1 15	1 35	1.45	1.45
Norfolk	0.45	0.72	0 93	1.30	1 60	1.65	1.75	0.37	0 65	0 82	1.10	1.30	1.40	1.40
Raleigh	0.45	0.78	1.00	1.48	1.65	1.80	1.80	0.38	0.65	0.86	1.15	1.43	1 45	1.47
Savannah	0.42	0.70	0 90	1.40	1.80	1.95	2.00	0.38	0 62	0 80	1.20	1 50	1 60	1 60
Atlanta	0 42	0.68	0 90	1.40	1.70	1.90	1.90	0.35	0 60	0 80	1.10	1.40	1 40	1 40
Little Rock	0.40	0 65	0.82	1.20	1.60	1.80	2.00	0.34	0 55	0 72	1.05	1.25	1.45	1 50
Fort Worth	0.42	0.70	0.95	1.35	1.60	1.90	1 90	0.36	0 63	0 82	1.17	1.36	1 50	1 50
Abilene	0.45	0.70	0.90	1.25	1.80	1.80	1.80	0.37	0.62	0.77	1.10	1.40	1.40	1.40
Bentonville	0 45	0.68	0 90	1.15	1.50	1.60	1.60	0.38	0.60	0.75	1.05	1.30	1.40	1.40
St. Louis	0.45	0.70	0.90	1.10	1.28	1.50	1.55	0.35	0 53	0 68	0.92	1 22	1 32	1 35
Kansas City	0.43	0.70	0.92	1.40	1.80	1.90	1.90	0.35	0 58	0.76	1.10	1.35	1.60	1 60
Lincoln	0.42	0.70	0.92	1.28	1.75	1.90	2.00	0.36	0 60	0.76	1 05	1.35	1.40	1.45
Des Moines	0.43	0 70	0.92	1.20	1 40	1 50	1 60	0 35	0.59	0 73	1.04	1.20	1 25	. .
Average	0.43	0.69	0.90	1.28	1.61	1.75	1.80	0 36	0.60	0 77	1.07	1.31	1 40	1.46

TABLE 14. — INTENSE PRECIPITATION EXCEEDED WITH GIVEN FREQUENCY AS DETERMINED FROM RECORDS OF INDIVIDUAL STATIONS — 1896–1914 inclusive — (*Continued*)

Station	Precipitation exceeded once in													
	2 Years							1 Year						
	Time in minutes							Time in minutes						
	5	10	15	30	60	100	120	5	10	15	30	60	100	120
Group No. 2														
New York	0.37	0.62	0.78	1.10	1.40	1.70	1.75	0.32	0.50	0.65	0.90	1.18	1.25	......
Philadelphia	0.40	0.68	0.88	1.15	1.50	1.50	1.55	0.35	0.57	0.77	0.97	1.10	1.20	....
Washington	0.44	0.70	0.90	1.45	1.70	1.88	1.88	0.38	0.65	0.80	1.15	1.35	1.45	1.45
Norfolk	0.45	0.72	0.93	1.30	1.60	1.65	1.75	0.37	0.65	0.82	1.10	1.30	1.40	1.40
Raleigh	0.45	0.78	1.00	1.48	1.65	1.80	1.80	0.38	0.65	0.86	1.15	1.43	1.45	1.47
Savannah	0.42	0.70	0.90	1.40	1.80	1.95	2.00	0.38	0.62	0.80	1.20	1.50	1.60	1.60
Atlanta	0.42	0.68	0.90	1.40	1.70	1.90	1.90	0.35	0.60	0.80	1.10	1.40	1.40	1.40
Little Rock	0.40	0.65	0.82	1.20	1.60	1.80	2.00	0.34	0.55	0.72	1.05	1.25	1.45	1.50
Fort Worth	0.42	0.70	0.95	1.35	1.60	1.90	1.90	0.36	0.63	0.82	1.17	1.36	1.50	1.50
Abilene	0.45	0.70	0.90	1.25	1.80	1.80	1.80	0.37	0.62	0.77	1.10	1.40	1.40	1.40
Bentonville	0.45	0.68	0.90	1.15	1.50	1.60	1.60	0.38	0.60	0.75	1.05	1.30	1.40	1.40
St. Louis	0.45	0.70	0.90	1.10	1.28	1.50	1.55	0.35	0.53	0.68	0.92	1.22	1.32	1.35
Kansas City	0.43	0.70	0.92	1.40	1.80	1.90	1.90	0.35	0.58	0.76	1.10	1.35	1.60	1.60
Lincoln	0.42	0.70	0.92	1.28	1.75	1.90	2.00	0.36	0.60	0.76	1.05	1.35	1.40	1.45
Des Moines	0.43	0.70	0.92	1.20	1.40	1.50	1.60	0.35	0.59	0.73	1.04	1.20	1.25	...
Average	0.43	0.69	0.90	1.28	1.61	1.75	1.80	0.36	0.60	0.77	1.07	1.31	1.40	1.46

TABLE 14. — INTENSE PRECIPITATION EXCEEDED WITH GIVEN FREQUENCY AS DETERMINED FROM RECORDS OF INDIVIDUAL STATIONS — 1896–1914 inclusive — (*Continued*)

Station	Precipitation exceeded once in													
	10 Years							5 Years						
	Time in minutes							Time in minutes						
	5	10	15	30	60	100	120	5	10	15	30	60	100	120
Group No. 3														
Boston	0.42	0.70	0.80	1.15	1.60	1.60	1.80	0.35	0.60	0.70	1.00	1.50	1.55	1.60
Albany	0.50	0.90	1.00	1.20	1.45	1.80	1.80	0.45	0.80	0.90	1.05	1.20	1.30	1.30
Pittsburg	0.50	0.70	0.90	1.20	1.60	1.60	1.60	0.42	0.65	0.75	1.05	1.40	1.40	1.45
Elkins	0.53	0.85	1.05	1.45	2.00	2.20	2.20	0.45	0.75	0.90	1.20	1.50	1.60	1.60
Asheville	0.55	0.90	1.10	1.40	1.80	2.20	2.40	0.50	0.85	0.98	1.20	1.55	1.70	1.80
Knoxville	0.48	0.80	1.05	1.60	1.80	2.00	2.00	0.42	0.70	0.98	1.38	1.50	1.60	1.70
Memphis	0.45	0.75	1.00	1.20	1.60	2.00	2.00	0.40	0.68	0.90	1.12	1.50	1.80	1.85
Cairo	0.45	0.80	1.00	1.50	2.00	2.60	2.70	0.39	0.69	0.90	1.40	1.80	2.20	2.40
Indianapolis	0.55	0.95	1.10	1.40	1.90	2.00	2.20	0.50	0.84	1.00	1.25	1.60	1.70	1.80
Cincinnati	0.48	0.78	1.00	1.60	2.00	2.10	2.20	0.40	0.65	0.80	1.20	1.50	1.60	1.80
Cleveland	0.55	0.90	1.00	1.40	1.60	1.80	1.80	0.45	0.75	0.88	1.30	1.40	1.50	1.50
Detroit	0.48	0.80	1.00	1.40	1.80	2.00	2.20	0.45	0.70	0.90	1.28	1.50	1.80	1.85
Grand Haven	0.45	0.70	1.00	1.40	1.60	1.60	1.60	0.40	0.60	0.90	1.20	1.40	1.40	1.40
Chicago	0.55	0.85	1.00	1.35	1.60	1.75	1.80	0.45	0.75	0.94	1.25	1.45	1.55	1.60
Madison	0.55	0.90	1.10	1.40	1.80	2.00	2.40	0.45	0.70	0.90	1.10	1.40	1.50	1.50
St. Paul	0.52	0.80	1.00	1.55	2.10	2.30	2.30	0.46	0.72	0.90	1.40	1.80	2.00	2.20
Moorhead	0.50	0.80	1.10	1.50	1.80	2.00	2.00	0.40	0.70	0.90	1.35	1.70	1.90	1.90
Yankton	0.50	0.80	1.00	1.50	1.80	2.00	2.00	0.44	0.70	0.90	1.30	1.65	1.80	1.80
Dodge	0.52	0.95	1.15	1.50	2.00	2.60	2.60	0.48	0.80	1.00	1.40	1.70	1.90	1.90
Average	0.50	0.82	1.02	1.41	1.78	2.01	2.08	0.43	0.72	0.90	1.23	1.53	1.67	1.73

TABLE 14. — INTENSE PRECIPITATION EXCEEDED WITH GIVEN FREQUENCY AS DETERMINED FROM RECORDS OF INDIVIDUAL STATIONS — 1896–1914 inclusive — (*Continued*)

Station	Precipitation exceeded once in													
	2 Years							1 Year						
	Time in minutes							Time in minutes						
	5	10	15	30	60	100	120	5	10	15	30	60	100	120
Group No. 3.														
Boston	0.30	0.45	0.60	0.87	1.00	1.30	1.35	...	...	...	...	...	...	...
Albany	0 37	0 60	0.70	0.90	1.10	1.10	...	0.32	0.50	0.60	...	...	...	...
Pittsburg	0 35	0.57	0.65	0.90	1.10	1 20	1 30	0.30	0 45	0 58		...	...	...
Elkins	0 38	0 65	0.80	1.05	1.20	1 20	1 30	0 33	0 56	0 65	0 85	.	..	...
Asheville	0.42	0 70	0.88	1.11	1.20	1.30	1 30	0 36	0.58	0 71	0 95	1.10	...	...
Knoxville	0 37	0.60	0.77	1.02	1.25	1.30	1.30	0 32	0.50	0.60	0 85	1 10	.	...
Memphis	0.35	0 57	0.74	1.04	1.30	1 40	1 45	0.31	0.52	0.66	0.90	1 10	1.10	...
Cairo	0.34	0.57	0 75	1.10	1.40	1.60	1 60	0 30	0 52	0 65	0 96	1 10	1 20	1.30
Indianapolis	0.40	0.68	0 90	1.15	1.40	1.50	1.50	0 35	0 60	0 80	0 96	1.10	...	..
Cincinnati	0 34	0 56	0 65	0 98	1.15	1.30	1 35	0.30	0 46	0 58	0.85		...	...
Cleveland	0 36	0 64	0 78	1 05	1.20	1.25	1 25	0 32	0.50	0 63	0 85	1 00	...	...
Detroit	0 40	0 63	0 76	1.05	1.20	1.30	1 30	0 32	0 50	0 65	0 80	1 00	..	...
Grand Haven	0.32	0 54	0.80	1 00	1 30	1.30	1.30	0.29	0.45	0 60	0 85	1 00	1 00	1.00
Chicago	0 36	0.64	0.80	1 05	1.28	1.30	1.30	0.30	0.50	0.65	0.88	1 00	...	...
Madison	0.35	0 60	0 70	1 00	1 15	1 20	1.20	0.30	0.47	0 62	0 85		...	...
St. Paul	0 42	0 64	0 80	1.10	1.45	1.55	1 60	0.33	0.52	0.65	0 90	1 15	...	.
Moorhead	0 33	0.52	0 80	1 10	1.40	1.60	1.60	0.30	0.50	0.70	0.90	1.10	1 20	1 20
Yankton	0.36	0 58	0.78	1.10	1.40	1.45	1.45	0.32	0 53	0.64	0.90	1.10	..	...
Dodge	0.40	0.68	0.85	1.20	1.50	1.55	1 55	0 32	0 52	0.65	1 00	1 25	1 30	..
Average	0.36	0 60	0 76	1.04	1.27	1.35	1.39	0.32	0 52	0 65	0.90	1.08	1.16	1 17

TABLE 14. — INTENSE PRECIPITATION EXCEEDED WITH GIVEN FREQUENCY AS DETERMINED FROM RECORDS OF INDIVIDUAL STATIONS — 1896–1914 inclusive — (*Concluded*)

Station	Precipitation exceeded once in													
	10 Years							5 Years						
	Time in minutes							Time in minutes						
	5	10	15	30	60	100	120	5	10	15	30	60	100	120
Group No. 4														
Duluth	0.45	0.80	1.00	1.40	1.60	2.00	2.10	0.43	0.75	0.90	1.10	1.47	1.60	1.60
Escanaba	0.45	0.80	0.90	1.15	1.30	1.60	1.80	0.38	0.58	0.65	0.85	1.10	1.25	1.40
Buffalo	0.45	0.70	0.90	1.20	1.60	1.60	1.60	0.38	0.62	0.80	1.13	1.30	1.30	1.30
Rochester	0.45	0.75	0.80	1.20	1.80	2.00	2.20	0.37	0.63	0.70	1.00	1.50	1.70	1.95
Average	0.45	0.76	0.90	1.24	1.57	1.80	1.93	0.39	0.64	0.76	1.02	1.34	1.46	1.56
	2 Years							1 Year						
Duluth	0.36	0.57	0.70	0.95	1.10	1.27	1.27	0.30	0.47	0.59	0.73	0.82	.....	......
Escanaba	0.32	0.45	0.58	0.80	0.95	1.00	1.00	0.25	0.40	0.50	....	..	....	.....
Buffalo	0.34	0.55	0.70	0.80	1.00	1.00	1.10	0.27	0.40				.	......
Rochester	0.30	0.50	0.62	0.75	1.00	1.20	1.20	0.24	0.38	0.50	0.65	0.75		.
Average	0.33	0.52	0.65	0.82	1.01	1.12	1.14	0.26	0.41	0.53	0.69	0.78		.
	10 Years							5 Years						
Group No. 5														
Denver	0.53	0.90	1.10	1.36	1.40	1.40	1.40	0.45	0.80	0.95	1.20	1.20	1.20	1.20
Bismarck	0.50	0.78	1.00	1.20	1.30	1.40	1.40	0.40	0.70	0.85	1.10	1.20	1.25	1.25
Average	0.51	0.84	1.05	1.28	1.35	1.40	1.40	0.42	0.75	0.90	1.15	1.20	1.22	1.22
	2 Years							1 Year						
Denver	0.37	0.54	0.80	0.95	1.00	1.00	..	0.25	0.40	0.55	0.70	.	.....	... ..
Bismarck	0.35	0.55	0.72	0.95	1.05	1.10	1.10	0.25	0.42	0.55	0.75	0.90		.
Average	0.36	0.54	0.76	0.95	1.02	1.05	1.10	0.25	0.41	0.55	0.72	0.90	.. .	. . ..

TABLE 15.—INTENSE PRECIPITATION EXCEEDED WITH GIVEN FREQUENCY AS DETERMINED BY MEYER FORMULAS

Group No. 1	Formulas		Precipitation in given number of minutes: 5		10		15		30		45		60		80		100		120	
Frequency	For am't	For rate	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour
Once in 1 year	$\frac{2.42\,t}{t+23}$	$\frac{145}{t+23}$	0 43	5 16	0 73	4 38	0 96	3 84	1 37	2 74	1 60	2 13	1 75	1 75	1 88	1 41	1 97	1 18	2 02	1 01
" " 2 years	$\frac{3.00\,t}{t+24.5}$	$\frac{180}{t+24\ 5}$	0.50	6.00	0 87	5.22	1.14	4 56	1 65	3 30	1 94	2 59	2 14	2 14	2 30	1 72	2 42	1 45	2 49	1 24
" " 5 "	$\frac{3.67\,t}{t+27}$	$\frac{220}{t+27}$	0 57	6 85	0 99	5 94	1 31	5 24	1 93	3 86	2 29	3 06	2 53	2 53	2 75	2 06	2 89	1 73	3 00	1 50
" " 10 "	$\frac{4.60\,t}{t+32}$	$\frac{276}{t+32}$	0 62	7 45	1 10	6 60	1 47	5 88	2 23	4 46	2 68	3 58	3 00	3 00	3 28	2 46	3 48	2 09	3 63	1 81
" " 25 "	$\frac{5.91\,t}{t+40}$	$\frac{355}{t+40}$	0 65	7 80	1 18	7 08	1 63	6 52	2 54	5 08	3 13	4 17	3 55	3 55	3 95	2 96	4 23	2 54	4 44	2 22
" " 50 "	$\frac{7.05\,t}{t+50}$	$\frac{450}{t+50}$	0 68	8 16	1.25	7 50	1 73	6.92	2 81	5 62	3 56	4 74	4 09	4 09	4 62	3 46	4 99	3 00	5 29	2 64
" " 100 "	$\frac{10.00\,t}{t+65}$	$\frac{600}{t+65}$	0 72	8 65	1.33	7 98	1 87	7 48	3 16	6 32	4 09	5 45	4 80	4 80	5 52	4 14	6 05	3 63	6 50	3.25

For location of Weather Bureau Stations from whose records of excessive precipitation the given formulas were derived, and for boundaries of areas to which they apply, see Fig. 139.

TABLE 15.—INTENSE PRECIPITATION EXCEEDED WITH GIVEN FREQUENCY AS DETERMINED BY MEYER FORMULAS—(*Continued*)

Group No. 2			Precipitation in given number of minutes																	
			5		10		15		30		45		60		80		100		120	
Frequency	Formulas: For am't	Formulas: For rate	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour
Once in 1 year	$\frac{1.67\,t}{t+18}$	$\frac{100}{t+18}$	0.36	4.32	0.60	3.60	0.76	3.04	1.04	2.08	1.19	1.59	1.28	1.28	1.36	1.02	1.41	0.85	1.45	0.72
" " 2 years	$\frac{2.18\,t}{t+21}$	$\frac{131}{t+21}$	0.42	5.04	0.71	4.26	0.91	3.64	1.29	2.58	1.48	1.98	1.62	1.62	1.73	1.30	1.80	1.08	1.86	0.93
" " 5 "	$\frac{2.85\,t}{t+23.5}$	$\frac{171}{t+23.5}$	0.50	6.00	0.85	5.10	1.11	4.44	1.60	3.20	1.87	2.50	2.05	2.05	2.20	1.65	2.31	1.39	2.38	1.19
" " 10 "	$\frac{3.57\,t}{t+26}$	$\frac{214}{t+26}$	0.57	6.85	0.99	5.94	1.30	5.20	1.91	3.82	2.26	3.02	2.50	2.50	2.69	2.02	2.83	1.70	2.93	1.46
" " 25 "	$\frac{4.20\,t}{t+28}$	$\frac{252}{t+28}$	0.63	7.56	1.11	6.66	1.47	5.88	2.17	4.34	2.58	3.45	2.86	2.86	3.10	2.33	3.28	1.97	3.41	1.70
" " 50 "	$\frac{4.81\,t}{t+30}$	$\frac{289}{t+30}$	0.69	8.28	1.21	7.26	1.62	6.48	2.40	4.80	2.89	3.85	3.20	3.20	3.50	2.63	3.71	2.22	3.86	1.93
" " 100 "	$\frac{5.41\,t}{t+32}$	$\frac{325}{t+32}$	0.73	8.76	1.30	7.80	1.73	6.92	2.63	5.26	3.17	4.22	3.53	3.53	3.86	2.90	4.10	2.46	4.28	2.14

TABLE 15.—INTENSE PRECIPITATION EXCEEDED WITH GIVEN FREQUENCY AS DETERMINED BY MEYER FORMULAS—(*Continued*)

Group No 3			Precipitation in given number of minutes																	
	....		5		10		15		30		45		60		80		100		120	
Frequency	Formulas: For am't	Formulas: For rate	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in per hour	Amount, inches	Rate, in per hour	Amount, inches	Rate, in per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour*	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in per hour
Once in 1 year	$\frac{1.20\,t}{t+13}$	$\frac{72}{t+13}$	0.33	3.96	0.52	3.12	0.64	2.56	0.84	1.68	0.93	1.24	0.99	*1.00* 0.99	1.04	0.78	1.06	0.63	1.08	0.54
" " 2 years	$\frac{1.60\,t}{t+16}$	$\frac{96}{t+16}$	0.38	4.56	0.62	3.72	0.78	3.12	1.04	2.08	1.18	1.57	1.26	*1.27* 1.26	1.33	1.00	1.38	0.83	1.41	0.70
" " 5 "	$\frac{2.03\,t}{t+18}$	$\frac{122}{t+18}$	0.44	5.28	0.73	4.38	0.92	3.68	1.27	2.54	1.46	1.94	1.56	*1.63* 1.56	1.65	1.24	1.72	1.03	1.77	0.88
" " 10 "	$\frac{2.50\,t}{t+19.5}$	$\frac{150}{t+19.5}$	0.51	6.12	0.85	5.10	1.09	4.36	1.51	3.02	1.74	2.32	1.89	*1.90* 1.89	2.01	1.51	2.10	1.26	2.15	1.07
" " 25 "	$\frac{3.02\,t}{t+21}$	$\frac{181}{t+21}$	0.58	6.96	0.98	5.82	1.25	5.00	1.78	3.56	2.06	2.74	2.24	*2.26* 2.24	2.38	1.79	2.49	1.49	2.57	1.28
" " 50 "	$\frac{3.60\,t}{t+23}$	$\frac{216}{t+23}$	0.64	7.68	1.09	6.55	1.42	5.68	2.04	4.08	2.38	3.18	2.61	*2.63* 2.61	2.80	2.10	2.94	1.76	3.02	1.51
" " 100 "	$\frac{4.27\,t}{t+25}$	$\frac{256}{t+25}$	0.70	8.40	1.22	7.32	1.60	6.40	2.32	4.64	2.74	3.66	3.01	*2.80* 3.01	3.25	2.44	3.42	2.05	3.53	1.76

* Figures in italics correspond to the equation Rate = $(1 + .9 \log t)$. Compare this with Fuller's equation $(1 + .8 \log T)$ for frequency of floods, see p. 365.

TABLE 15. — INTENSE PRECIPITATION EXCEEDED WITH GIVEN FREQUENCY AS DETERMINED BY MEYER FORMULAS — (*Continued*)

Group No. 4			Precipitation in given number of minutes: 5		10		15		30		45		60		80		100		120	
Frequency	Formulas: For am't	For rate	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour
Once in 1 year	$\frac{1.00t}{t+15}$	$\frac{60}{t+15}$	0.25	3.00	0.40	2.40	0.50	2.00	0.66	1.32	0.75	1.00	0.80	0.80	0.81	0.63	0.88	0.53	0.88	0.44
" " 2 years	$\frac{1.40t}{t+16}$	$\frac{84}{t+16}$	0.33	4.00	0.54	3.24	0.68	2.72	0.91	1.82	1.01	1.38	1.10	1.10	1.17	0.88	1.21	0.73	1.23	0.62
" " 5 "	$\frac{1.80t}{t+17.5}$	$\frac{108}{t+17.5}$	0.40	4.80	0.66	3.96	0.83	3.32	1.14	2.28	1.30	1.73	1.40	1.40	1.48	1.11	1.53	0.92	1.57	0.78
" " 10 "	$\frac{2.20t}{t+19}$	$\frac{132}{t+19}$	0.46	5.52	0.76	4.56	0.97	3.88	1.35	2.70	1.55	2.06	1.67	1.67	1.77	1.33	1.85	1.11	1.90	0.95
" " 25 "	$\frac{2.67t}{t+20}$	$\frac{160}{t+20}$	0.53	6.36	0.89	5.34	1.15	4.60	1.60	3.20	1.85	2.46	2.00	2.00	2.14	1.60	2.22	1.33	2.28	1.14
" " 50 "	$\frac{3.10t}{t+21}$	$\frac{186}{t+21}$	0.60	7.20	1.01	6.06	1.29	5.16	1.83	3.66	2.12	2.82	2.30	2.30	2.46	1.84	2.56	1.54	2.64	1.32
" " 100 "	$\frac{3.50t}{t+22}$	$\frac{210}{t+22}$	0.65	7.80	1.10	6.60	1.42	5.68	2.02	4.04	2.35	3.13	2.58	2.58	2.75	2.06	2.87	1.72	2.96	1.48

TABLE 15.—INTENSE PRECIPITATION EXCEEDED WITH GIVEN FREQUENCY AS DETERMINED BY MEYER FORMULAS—(*Concluded*)

			Precipitation in given number of minutes																	
Group No. 5.	. .. .		5		10		15		30		45		60		80		100		120	
Frequency	Formulas		Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour
	For am't	For rate																		
Once in 1 year.	$\frac{1.00\,t}{t+13}$	$\frac{60}{t+13}$	0 28	3 36	0 44	2 64	0 54	2 16	0 70	1 40	0 77	1 03	0 82	0 82	0 85	0 64	0 88	0 53	0 90	0 45
" " 2 years.......	$\frac{1.25\,t}{t+13}$	$\frac{75}{t+13}$	0 35	4.20	0.54	3.24	0.67	2 68	0 88	1 76	0 97	1 29	1 03	1 03	1 08	0 81	1 11	0 67	1 13	0 56
" " 5 "	$\frac{1.50\,t}{t+13}$	$\frac{90}{t+13}$	0.42	5.04	0 65	3.90	0 80	3 20	1 05	2 10	1 16	1 55	1 24	1 24	1 29	0 97	1 33	0.80	1 35	0 68
" " 10 "	$\frac{1.75\,t}{t+13}$	$\frac{105}{t+13}$	0 49	5.88	0.76	4 56	0 94	3 76	1.22	2 44	1 36	1 81	1 44	1 44	1 51	1 13	1 55	0 93	1 58	0 79
" " 25 "	$\frac{2.10\,t}{t+14}$	$\frac{126}{t+14}$	0 55	6.60	0.87	5 22	1.09	4.36	1 44	2 88	1 61	2.14	1 71	1 71	1 79	1 34	1 85	1.11	1 88	0 94
" " 50 "	$\frac{2.53\,t}{t+16}$	$\frac{152}{t+16}$	0.60	7 20	0.98	5 88	1 23	4 92	1 65	3 30	1 87	2 49	2 00	2 00	2 11	1 58	2 19	1 32	2 23	1 12
" " 100 "	$\frac{3.00\,t}{t+18}$	$\frac{180}{t+18}$	0.65	7.80	1.07	6 42	1 37	5.48	1.87	3.74	2 14	2 86	2 31	2 31	2 45	1 84	2 54	1.52	2.61	1 30

TABLE 16.—COMPARISON OF RAINFALL FORMULAS

Locality to which formula applies	Formula proposed: By	Formula proposed: Date	Conditions represented by formula	Formula	Corresponding Meyer formulas (Table 15)	5 min: Amount, inches	5 min: Rate, in. per hour	10 min: Amount, inches	10 min: Rate, in. per hour	15 min: Amount, inches	15 min: Rate, in. per hour	30 min: Amount, inches	30 min: Rate, in. per hour	60 min: Amount, inches	60 min: Rate, in. per hour	120 min: Amount, inches	120 min: Rate, in. per hour
1. Eastern U. S.	Talbot	1891	Maximum	$i=\frac{360}{t+30}$	Groups 2, 3 and 4	0.86	10.29	1.50	9.00	2.00	8.00	3.00	6.00	4.00	4.00	4.80	2.40
2. Eastern U. S.	Talbot	1891	Ordinary	$i=\frac{105}{t+15}$	Groups 2, 3 and 4	0.44	5.25	0.70	4.20	0.88	3.50	1.16	2.33	1.40	1.40	1.56	0.78
3. New England & New York	Metcalf & Eddy	1914	Once in 10 years	$i=\frac{12}{t^{0.5}}$	Groups 2, 3 and 4	0.45	5.36	0.63	3.80	0.78	3.10	1.09	2.19	1.55	1.55	2.18	1.09
4. Boston, Mass.	Dorr	1892	Basis of design	$i=\frac{150}{t+30}$	Group 3	0.36	4.28	0.62	3.75	0.83	3.33	1.25	2.50	1.67	1.67	2.00	1.00
5. Boston, Mass.	Kuichling	1905	Basis of design	$i=\frac{106}{t+13}$	Group 3	0.49	5.89	0.77	4.61	0.95	3.79	1.23	2.46	1.44	1.44	1.60	0.80
6. Boston, Mass.	Kuichling	1905	Basis of design	$i=\frac{120}{t+20}$	Group 3	0.40	4.80	0.67	4.00	0.86	3.43	1.20	2.40	1.50	1.50	1.72	0.86
7. Boston, Mass.	Sherman	1905	Maximum	$i=\frac{38.64}{t^{0.687}}$	Group 3	1.07	12.80	1.32	7.95	1.50	6.01	1.87	3.74	2.31	2.31	2.88	1.44
8. Boston, Mass.	Sherman	1905	Basis of design (max.)	$i=\frac{25.12}{t^{0.687}}$	Group 3	0.69	8.32	0.86	5.17	0.98	3.91	1.22	2.43	1.51	1.51	1.86	0.93
9. Boston, Mass.	Metcalf & Eddy	1911	Basis of design (max.)	$i=\frac{15.5}{t^{0.5}}$	Group 3	0.58	6.93	0.82	4.90	1.00	4.00	1.42	2.83	2.00	2.00	2.82	1.41
10. Philadelphia, Pa.	Bureau of surveys	1911	Maximum	$i=\frac{27}{t^{0.5}}$	Group 2	1.01	12.07	1.42	8.54	1.75	6.99	2.47	4.94	3.49	3.49	4.92	2.46
11. Philadelphia, Pa.	Bureau of surveys	1911	High	$i=\frac{18}{t^{0.5}}$	Group 2	0.67	8.05	0.95	5.69	1.16	4.65	1.64	3.29	2.32	2.32	3.28	1.64

TABLE 16. — COMPARISON OF RAINFALL FORMULAS — (*Continued*)

Locality to which formula applies	Formula proposed		Conditions represented by formula	Formula	Corresponding Meyer formulas (Table 15)	Time in minutes											
						5		10		15		30		60		120	
	By	Date				Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour	Amount, inches	Rate, in. per hour
12. Philadelphia, Pa.	Bureau of surveys	1911	Ordinary	$i=\frac{9}{t^{0.5}}$	Group 2	0 34	4 02	0 47	2 84	0 58	2 32	0 82	1 64	1 16	1 16	1 64	0 82
13. Baltimore, Md.	Hendrick	1911	Maximum	$i=\frac{300}{t+25}$	Group 2	0 83	10 00	1 43	8 58	1 88	7 50	2 74	5 47	3 54	3 54	4 14	2 07
14. Baltimore, Md.	Hendrick	1911	Basis of design	$i=\frac{105}{t+10}$	Group 2	0 58	7.00	0 88	5 25	1 05	4 20	1 32	2 63	1 50	1 50	1 62	0 81
15. Savannah, Ga.	de Bruyn-Kops	1908	Maximum	$i=\frac{191}{t+19}$	Group 2	0 66	7 95	1 10	6 58	1 40	5 61	1 94	3 89	2 42	2 42	2 76	1 38
16. Savannah, Ga.	de Bruyn-Kops	1908	Once in 2 years	$i=\frac{163}{t+27}$	Group 2	0 42	5 10	0 74	4 41	0 97	3 88	1 43	2 86	1 88	1 88	2 22	1 11
17. Savannah, Ga.	de Bruyn-Kops	1908	Once a year	$i=\frac{141}{t+27}$	Group 2	0 37	4 41	0 64	3 82	0 84	3 36	1 24	2 47	1 63	1 63	1 92	0 96
18. Chicago, Ill.	Hill	about 1907	....	$i=\frac{120}{t+15}$	Group 3	0 50	6 00	0 80	4 80	1 00	4 00	1 34	2 67	1 60	1 60	1 78	0 89
19. Louisville, Ky.	Metcalf & Eddy	1911	....	$i=\frac{14}{t^{0.5}}$	Group 3	0 52	6 26	0 74	4 42	0 90	3 61	1 28	2 56	1 81	1 81	2 56	1 28
20. New Orleans, La.	Metcalf & Eddy	1911	....	$i=\frac{19}{t^{0.05}}$	Group 1	0 71	8 50	1 00	6 00	1 23	4 91	1 74	3 47	2 45	2 45	3 46	1 73
21. St. Louis, Mo.	Horner	1910	... .	$i=\frac{56}{(t+5)^{0.85}}$	Group 2	0 67	8 00	0 93	5 60	1 10	4 39	1 36	2 73	1 61	1.61	1 86	0.93
22. Denver, Colo.	Metcalf & Eddy	1911	....	$i=\frac{84}{(t+4)}$	Group 5	0 78	9 33	1 00	6 00	1 10	4 42	1 24	2 47	1 31	1 31	1 36	0 68

CHAPTER V

EVAPORATION FROM WATER SURFACES

The Water Cycle. — A quantity of water just equal to the precipitation which falls upon the land and water areas of the earth's surface in the course of several years must be evaporated again, otherwise there would have to be a progressive change in the vapor content of the air or an escape of water vapor from the upper atmosphere into space. Even our limited meteorological observations and our knowledge of gases, however, indicate that neither of these possibilities is a fact. As the variable amount of moisture in the earth's atmosphere represents but a fraction of an inch of precipitation, it follows that for the earth as a whole, precipitation and evaporation are two stages in a cycle of phenomena that has neither beginning nor end, but which may possibly be experiencing a small progressive increase or decrease.

If the mean annual surface temperature of the earth is assumed to be constant, those factors which tend to increase evaporation from the land area will also tend to increase precipitation.

Under the conditions of constant temperature, humidity and wind, evaporation from the large water surfaces of the earth must remain constant.

A temporary increase in temperature results in increased evaporation and also increased precipitation. This is well shown in Fig. 48, p. 73, which gives the effect of changes in temperature in eastern United States on precipitation in Europe.

If changes occur in the cultural conditions of the large land areas which increase evaporation, the result must inevitably be an increase in precipitation. On the other hand, if there are changes on the land areas which increase the amount of water which runs off over the earth's surface, or through the rock strata,

into the ocean, evaporation and consequently precipitation, must be reduced.

So long as there is any runoff from the land areas, evaporation from the water areas of the earth's surface must exceed precipitation upon those areas, and, on the other hand, evaporation from the land areas must be less than the precipitation upon those areas. It follows, then, that the runoff from the land area represents the excess of evaporation from the water area over precipitation upon that area. As by far the greater portion of the water evaporated from the land area is re-precipitated upon that area, and as precipitation and evaporation over the water area remain substantially constant, the total runoff from the land area into the ocean must also remain substantially constant, irrespective of changes upon the land area which increase or decrease evaporation from that area. The distribution of the total runoff will, of course, be changed. In the region of prevailing westerlies watersheds lying on the easterly side of the continents will be principally affected by such changes in evaporation and precipitation.

Low- and high-pressure areas pass across the United States with average intervals of about 1000 miles in distance between them. As about 50 per cent of the evaporation from land occurs within three days after precipitation, most of the excess evaporation (assuming changes have occurred on the land area which have increased evaporation) will occur under the succeeding high and the moisture so evaporated will blow in toward the preceding low and be re-precipitated. Evidently a portion of any such possible increased evaporation over the eastern 500 miles, say, of the United States, would result in increased precipitation over the Atlantic Ocean. This, in turn, would slightly decrease evaporation from the ocean and to this extent, only, reduce runoff from the land area.

In view of these considerations, the difficulties attendant upon all efforts to find the effects of deforestation and cultivation and similar changes upon any given watershed, reflected

in the flow of streams draining such watersheds, can be better appreciated.

Of the precipitation which falls upon the land areas, a portion is evaporated; another portion is transpired by plants or used to form vegetable tissue; and still another portion of the precipitation runs off from the surface of the land area through water courses or finds its way back to the sea through the earth and rock strata.

Evaporation Defined. — Evaporation is the process by which water is changed from the liquid or the solid into the gaseous state. As temperature is but a measure of the average rate of motion of the molecules of any substance, it follows that some molecules are always moving at a much higher velocity than the average. Some of these extra-rapidly moving molecules are "bombarded" out through the surface film of water, into the atmosphere, so far beyond the influence of the force of cohesion that they do not return to the liquid, but remain in the space above as vapor. When the vapor over the water surface is relatively dense, some of the vapor molecules are caught in the water and join the liquid again. When the interchange of molecules is equal, evaporation is zero. This occurs when the dew-point temperature of the vapor above the water is just equal to the temperature of the liquid. While the dew-point temperature of the vapor is lower than the temperature of the water, evaporation continues, but when it is higher, condensation occurs. For any given temperature, the fewer the number of molecules of vapor in a unit volume of space above the water surface, the more rapid the rate at which the upward moving molecules are lost from the liquid.

Inasmuch as the process of evaporation consists of the abstraction of the more rapidly moving molecules from the liquid mass, it follows that the average rate of motion of the remaining molecules must be reduced and, consequently, the temperature of the liquid lowered. In other words, evaporation "is a process of cooling."

Effect of Temperature. — In discussing the subject of vapor pressure, it was pointed out that the pressure of saturated vapor doubles for every increase of from 15° to 20° F. in temperature. For the ordinary annual range of temperature, then, the pressure of saturated vapor will vary several hundred per cent.

It was first pointed out by Dalton, over a century ago, that the rate of evaporation from a water surface, other conditions remaining constant, varies nearly as the difference between the maximum vapor pressure corresponding to the temperature of the water and the actual pressure of vapor present in the atmosphere above the water. Vapor diffuses itself through the atmosphere somewhat slowly on account of the presence of the molecules of the dry gases. The principal means for the removal of the vapor which forms over all moist surfaces, is the bodily motion of the atmosphere. Since the air movement within a few feet of the land and water surface is very much slower than at higher elevations, there is always a considerable variation in the water vapor content of the lower few feet of the atmosphere. This variation consists not only of a variation in the relative humidity but in the actual amount of vapor present, as represented by the vapor pressure.

If we accept the principle enunciated by Dalton, that evaporation is governed by the difference between the vapor pressure corresponding to the water temperature and the actual pressure of the vapor present in the air above, and if the rate of reduction in the vapor content of the air from the earth's surface upward is uniform, it follows that the vapor pressure measured at almost any elevation above the earth's surface, when subtracted from the vapor pressure corresponding to the water temperature, will give a measure of evaporation. This is substantiated by the observations of Bigelow.*

Inasmuch as the maximum vapor pressure is a function of the temperature, the actual pressure of the vapor present in the

* Bigelow, Frank H., A Manual for Observers in Climatology and Evaporation: U. S. Weather Bureau, 1909, p. 33.

atmosphere must also be a function of the temperature, if the relative humidity remains constant. In other words, the rate of evaporation, according to Dalton's law, is approximately doubled for each 18 degrees rise in temperature, for constant humidity and wind velocity. Within the range of variation in monthly mean temperature occurring throughout most of the United States, the monthly mean rate of evaporation of free moisture will vary about 700 to 1200 per cent due to temperature changes alone.

Effect of Barometric Pressure. — Several of the early writers concluded that evaporation varied inversely as the barometric pressure. The same allowance was made by Russell in his evaporation formula first published in the Monthly Weather Review in 1888.

Stefan, in 1873, represented the effect of barometric pressure by the following expression: $\log\left(\frac{P}{P-p}\right)$ where P = barometric pressure and p = maximum vapor pressure at the given temperature. (The value of this expression becomes infinity at the boiling point.)

Fig. 140 shows the effect of barometric pressure on evaporation according to the formulas of Stefan and Russell. The two formulas give almost identical results for all temperatures.

Bigelow,* in his evaporation formula, completely neglects the effect of barometric pressure on evaporation, but in the discussion of his formula he does not state the reason why.

Note: It is evident that widely divergent views respecting the effect of barometric pressure on evaporation are held by different investigators. It appears to the author that even though water boils freely at temperatures less than 212° F. under less than sea-level barometric pressure, it does not necessarily follow that reduction in barometric pressure, *per se*, increases evaporation. To say that, under any given pressure, water boils at a given temperature, is merely another way of saying that the total pressure of the atmosphere, *i.e.*, the combined pressure of the nitrogen, oxygen, CO_2, water vapor, etc., are exactly equal to the maximum vapor pressure of the water at the temperature of the boiling point under those conditions. If the latent heat of vaporization

* Bigelow, Frank H., Atmospheric Circulation and Radiation, p. 346.

of water were zero, it would instantaneously pass from the liquid to the gaseous state when the boiling temperature was reached.

The various gases of the atmosphere exist independently of each other, except in so far as they retard the diffusion of other gases. Neither exerts a pressure on the other. While the distribution of oxygen and nitrogen in the atmosphere are governed, primarily, by the laws of Boyle and Charles, the distribution of water vapor is governed, primarily, by temperature. If, as

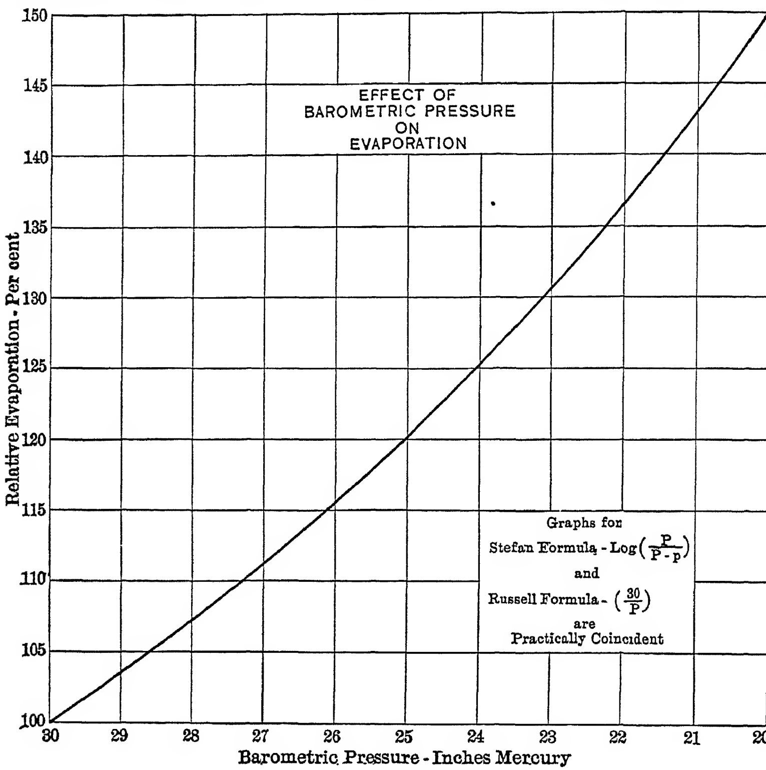


Fig. 140.

stated by Prof. Thomas Tate, vapor can diffuse itself through the other gases of the atmosphere more rapidly than it is formed from the surface of the water, it stands to reason that the total weight of the other gases above the water surface can have no material bearing upon the rate of evaporation, even though it has an effect upon the rate of diffusion and, particularly, upon the temperature at which water passes *freely* from the liquid to the gaseous state.

The author has in hand some experimental studies on the rate of evaporation from water in enclosed vessels in both quiet and circulating air, simulating, so far as possible, open air conditions. While these studies are incomplete, yet, they indicate only a small increase in the rate of evaporation even for one-third reduction in barometric pressure.

It would seem that if vapor can diffuse through the ordinary calm atmosphere more rapidly than it can form at the water surface, under ordinary open air temperatures, and if, moreover, vapor is usually carried away bodily by air currents still more rapidly than it can diffuse through the air, a reduction in barometric pressure — which is simply the removal of some of the molecules of nitrogen and oxygen which are in the path of the upward moving water vapor molecules — at best can only result in reducing the number of molecules of water vapor per cubic foot of space above the water. In other words, it can only result in a reduction of the *actual vapor pressure* above the water. Since the Dalton formula for evaporation, which the author has accepted, assumes evaporation to vary as the difference between the maximum vapor pressure at the water temperature and the actual vapor pressure in the air above the water, any effect of barometric pressure will have been taken into consideration, when the actual vapor pressure above the water surface has been determined.

The water vapor in the atmosphere is almost continually in a state of unstable equilibrium. The vapor pressure at the earth's surface is usually at least 5 to 10 times the weight of the column of vapor above; hence, the water vapor at the surface can be held in equilibrium only by the obstruction presented by the molecules of nitrogen and oxygen.

As the vapor moves upward, or is carried up by air currents, it cools and precipitates; consequently, there is a continual flow of water vapor to higher altitudes. A reduction in barometric pressure would facilitate this flow of vapor, and hence would tend to lower the relative humidity at the water surface, but would not affect evaporation in any direct way. If the flow of vapor upward is entirely dependent upon the bodily motion of the air, a reduction in barometric pressure could not affect evaporation, even in this indirect way.

The author desires to reiterate that these conclusions are based upon uncompleted laboratory studies and library researches, and must not be considered final from his viewpoint.*

Effect of Relative Humidity. — Relative humidity affects evaporation only in so far as, when taken in connection with temperature, it is a measure of the amount of vapor present in the atmosphere. If the temperature of the water is higher than the temperature of the air, evaporation will continue even though the relative humidity a few feet above the water surface is 100 per cent.

For the condition of uniform and constant air and water temperature, evaporation is proportional to the saturation deficit. It is equal to a constant times the maximum vapor pressure corresponding to the temperature, times one minus the relative humidity.

* Limited by time and funds, the author was unable to carry the studies mentioned to a satisfactory conclusion but at this writing he still considers the reasoning sound. A. F. M., 1927.

Figs. 28 and 29, pp. 54 and 55, show graphically the variation in monthly mean relative humidity at a number of stations distributed through the United States outside of the arid region of the West. It will be noted from these figures, that the monthly values of relative humidity in the several states vary by only about 15 to 20 per cent during the open season. Other conditions remaining constant, monthly mean evaporation, as the result of changes in monthly mean relative humidity, would vary only from 30 to 50 per cent.

Effect of Wind Velocity. — The effect of air movement on evaporation has been given widely different weights by different writers. Weilenmann, Stelling, and Tate hold that evaporation varies, approximately, directly as the wind velocity. DeHeen, Shierbeck and Svenson hold that it varies as the square root of the wind velocity. Russell found a wind effect which, for wind velocities up to 15 or 20 miles per hour, can be approximately represented by the expression $\left(1+\frac{w}{4}\right)$, where w represents wind velocity in miles per hour.

FitzGerald * found that the wind effect could be represented by the coefficient $1+\frac{w}{2}$.

Bigelow,† first used a wind factor represented by about $\left(1+\frac{w}{35}\right)$. Later‡ he used factors equivalent to $\left(1+\frac{w}{8.9}\right)$ and $\left(1+\frac{w}{7.4}\right)$. His expression was in the form of $(1+.084\,w)$ where w is in kilometers per hour.

The allowance to be made for change in wind velocity necessarily depends largely upon the elevation of the anemometer with reference to the surface from which evaporation is being measured. In so far as the author has had access to the original

* FitzGerald, Desmond, Trans. Am. Soc. C. E., XV, p. 581.

† Bigelow, Frank H., A Manual for Observers in Climatology and Evaporation, p. 28.

‡ Atmospheric Circulation and Radiation, p. 346, and Bulletin No. 2, Argentine Meteorological Office, p. 39.

published results, it would appear that the wind effects above referred to had been based upon a wind velocity observed at the elevation of the water surface in the basin from which evaporation was measured. The practicing engineer, however, is usually limited to wind velocity as observed by the U. S. Weather Bureau, which, in general, represents a velocity about twice that at the surface of the ground.

The effect of wind velocity on the evaporation of moisture from a broad expanse would appear to be primarily its effect in removing the vapor which forms more rapidly over the water surface than it can diffuse through the atmosphere above. If the rate of evaporation is determined by the vapor pressure gradient between the water surface and the upper atmosphere, it is not at all clear why, when the actual pressure of vapor present in the air a certain distance above the water has been determined, the effect of wind velocity has not already been taken account of. The effect of wind is to lower the relative humidity at the point of observation, if this is within a few feet of the water surface. Where a small surface of water is exposed to evaporation in quiescent air, a blanket of vapor soon forms above the water, which greatly reduces evaporation. If, under these conditions, however, a measurement of relative humidity is made rather close to the water surface, it will be found that the space is occupied by nearly saturated vapor. If the air is next set in motion, there will be a decided increase in the rate of evaporation which will also be indicated, however, by a great drop in relative humidity. Observations of relative humidity made at some distance from the water surface would not reflect the wind effect; consequently, it would appear correct to make an allowance for wind effect on the evaporation of moisture from small or non-uniformly moist surfaces when relative humidity is observed in a standard Weather Bureau shelter nearby, but to make no allowance for wind effect when the observations for relative humidity are made above a large water surface.

After comparing observed and computed evaporation from pans

at a number of stations, using various wind factors, the author has adopted $\left(1 + \frac{w}{10}\right)$ as a convenient measure of substantially the correct effect of wind on the evaporation of free moisture from water surfaces, when w represents wind velocity in miles per hour, as observed by the Weather Bureau, and for velocities less than 15 miles per hour. For higher velocities the wind effect becomes relatively less and less until a limit is reached at perhaps 25 miles per hour as Horton has shown.*

Using a wind factor of $\left(1 + \frac{w}{10}\right)$ the variation in evaporation due to change in monthly mean wind velocity as shown graphically in Fig. 22, page 37, for a number of states, amounts to only about 20 to 30 per cent.

Parshall† gives the formula $e = (0.44 + 0.118\,w)\ (V - v)$ for evaporation from a pan set in the ground, where v is measured within one inch of the water surface and w about a foot higher.

For W measured at Weather Bureau stations and using the author's form for monthly evaporation this formula reduces to approximately $E = 13.2\ (V - v)\left(1 + \frac{W}{7.5}\right)$.

Sleight‡ gives the formula $w = \frac{W}{.033\ H + 0.93}$ for reducing wind velocity observed at an elevation of H feet (H must be less than 50) above the ground to wind velocity two feet above the ground. Applying this factor to Parshall's formula in order to reduce w to wind observations at Weather Bureau stations about 30 feet above the general level of the ground or buildings, results in the term $0.118\ w$ becoming substantially $.06\ W$.

Perry§ gives the mean evaporation from a land pan at Christiansted, Virgin Islands, by months for the period 1919–1923. Wind velocity was observed at some distant point. Considering the months of June to October, when the temperature was prac-

* Eng. News-Record, April 26, 1917.

† Ralph L. Parshall, p. 325, Trans. Am. Soc. C. E., 1927.

‡ R. B. Sleight, p. 316, Trans. Am. Soc. C. E., 1927.

§ Lynn Perry, p. 317, Trans. Am. Soc. C. E., 1927.

tically constant and the relative humidity probably also quite constant, a practically constant value for 15 $(V - v)$ is found when using the author's wind factor.

Month	Observed evaporation	Mean temperature	Wind velocity	15 $(V - v)$
June........	7 65	81 1	10.1	3 80
July........	8 00	81 4	10.6	3.88
Aug.........	7.58	81.8	9.8	3.83
Sept.........	6.70	81.8	8.0	3.72
Oct..........	6.02	81.0	6.0	3.76
				3.80

On the basis of extensive experiments Horton has recently published a new formula for evaporation.* Reduced to its working form for a standard class " A " Weather Bureau evaporation pan, 4 feet in diameter, this formula reduces to:

$$E = .4\,(\psi - h)\,V$$

E = Evaporation in inches per 24 hours.

V = Vapor pressure corresponding to water surface temperature.

h = Relative humidity, measured close to the water surface and expressed decimally.

ψ = A wind factor to be taken from Horton's diagram on page 197 of the reference cited or from the following table prepared from that diagram:

Wind velocity, miles per hour	Wind factor ψ	Wind velocity, miles per hour	Wind factor ψ
0	1.0	11	1.89
1	1.18	12	1.91
2	1.34	13	1.92
3	1.46	14	1.94
4	1.56	15	1.95
5	1.63	16	1.96
6	1.70	17	1.97
7	1.75	18	1.97
8	1.80	19	1.98
9	1.83	20	1.98
10	1.86	25	1.99
		30	2.00

* Eng. News-Record, April 26, 1917.

The wind velocity is to be taken at a height of 1 foot above the ground or water surface, or to be reduced to that value in accordance with a table given by Horton. A wind velocity of 10 miles per hour, observed by the Weather Bureau stations at elevations approximately 30 feet above the level of the surrounding country or the roofs of the adjoining buildings, would correspond to a velocity of about $6\frac{1}{2}$ miles per hour at the ground level according to Horton.

For a large water surface, the actual vapor pressure, a few millimeters above the water surface, becomes equal to the maximum vapor pressure at the water surface temperature, when air and water are at the same temperature. Therefore, Horton's formula for evaporation from a lake or reservoir (except for a negligibly small marginal area) becomes:

$$E = .4\,(\psi - 1)\,V.$$

On page 211 the author pointed out that evaporation appears to depend upon the vapor pressure gradient above the water surface.

Since vapor removal from a lake surface depends primarily on wind action, it is apparent that a formula for evaporation from a lake may conceivably omit either wind velocity or relative humidity and still give correct results. Horton's formula omits relative humidity. This is an advantage since values of relative humidity observed over large lakes and reservoirs are seldom available. On the other hand, the assumption that air and water temperatures are equal is bound to lead to substantial errors in the light of such observed data as those graphically presented in Figs. 144 to 148 and 151. Differences between spring and fall evaporation, shown in these Figures, for the same temperature unquestionably result from differences in air and water temperature, as well as differences in relative humidity and wind velocity. For that reason the author prefers to use curves similar to those of Fig. 150 for determining evaporation from lakes and reservoirs for which complete meteorological data are not available.

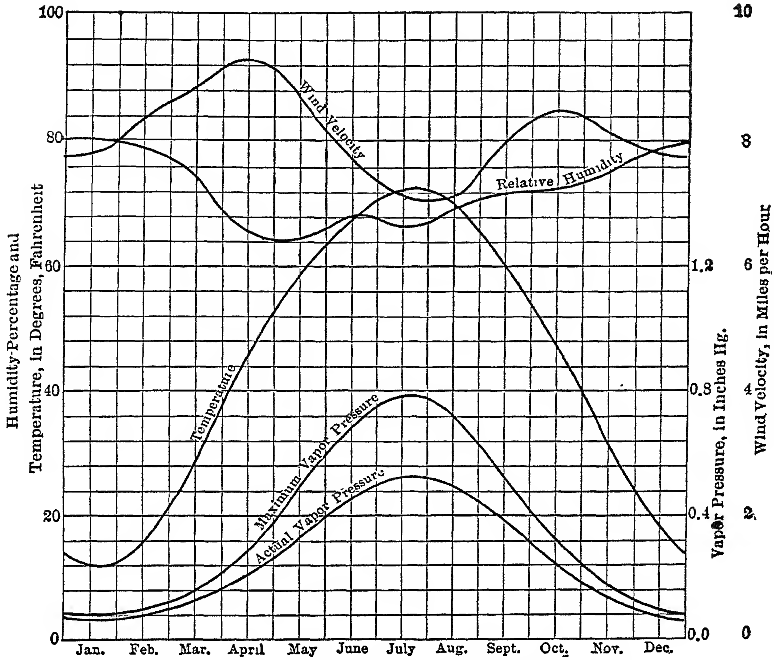


FIG. 141. — Monthly Mean Climatological Data, St. Paul, Minn.

Relative Effects. — Fig. 141 shows the monthly mean relative humidity, wind velocity, air temperature, maximum vapor pressure and actual vapor pressure in the atmosphere at St. Paul, Minn. Neither relative humidity nor wind velocity, it will be observed, varies between wide limits. The difference between the maximum and actual vapor pressure, however, *i.e.*, the variation in the factor which virtually determines evaporation, shows a variation of several hundred per cent.

Evaporation Formulas.*— The literature bearing on the subject of evaporation is very extensive. The most complete bibliography published to date is that prepared for the Monthly Weather Review of 1908 and 1909 by Mrs. Grace Livingston. It covers 849 references between the dates of 1670 and 1909.

A large number of evaporation formulas have been proposed, but aside from the Dalton law already mentioned, specific

* See pages 212–214 for Parshall's and Horton's Formulas.

reference will be made here to only two formulas, namely Bigelow's and Russell's. A full discussion of the data and considerations underlying Bigelow's formula is given in Bulletin No. 2 of the Argentine Meteorological Office published in 1912. Bigelow's formula for evaporation from a large water surface is:

$$E = 0.023 \frac{e_s}{e_d} \frac{de}{dS} (1 + 0.07\, w),$$

where E = the evaporation in centimeters during four hours time;

e_d = the vapor pressure in millimeters at the dew-point temperature of the air;

e_s = the vapor pressure at the water temperature;

w = the wind velocity at the surface of the water in kilometers per hour;

$\frac{de}{dS}$ = the rate of change in the maximum vapor pressure with temperature.

Russell's evaporation formula, fully discussed by him in the Monthly Weather Review of September, 1888, is:

$$E = \frac{30}{b} \left\{ A p_w + B(p_w - p_d) \right\},$$

E = evaporation in inches per month;

p_w = vapor tension, in inches of mercury, corresponding to monthly mean wet-bulb temperature;

p_d = vapor tension, in inches of mercury, corresponding to monthly mean dew-point temperature;

b = mean barometric pressure, in inches of mercury;

A = 1.96;

B = 43.88.

The values for A and B were derived by the method of least squares, from the Piché evaporometer observations for June, 1888, at the 18 stations listed in Table 17.

TABLE 17. — RUSSELL'S PICHÉ EVAPOROMETER OBSERVATIONS

Station	Temperature in degrees Fahrenheit	Evaporation in inches depth	Relative humidity, per cent	Wind velocity in miles per hour	Barometer in inches mercury
Boston	66.8	5.16	65 0	10.2	29.8
New York	71 4	4.49	67 6	8.3	29.7
Washington	73 0	4.64	68.0	4.8	29.8
Cincinnati	74.2	6.22	56.6	6.1	29.3
Memphis	75.4	4.33	70.8	4.8	29.6
New Orleans	77.3	3.82	77.7	6.8	29.9
Chicago	67.4	5.59	64.1	10.3	29.2
St. Louis	73.2	6.18	68.5	9.7	29.3
Keeler	73 9	11.66	23.0	7.9	26.2
Yuma	85 6	13.87	25.3	7.3	29.6
El Paso	83 0	13.91	24 1	8.2	26.1
Dodge City	74.5	7.80	53.0	11.6	27.3
San Antonio	78 0	2.76	75.3	8.1	29.1
Omaha	70 0	7.01	63 2	7.6	28.7
Denver	68.4	9.42	31 4	8.0	24.7
St. Vincent	62.8	5.63	69.5	7.6	28.9
Helena	58.8	4.88	56.6	7.9	25.7
Boise City	64.2	5.83	48.8	3.1	27.0

With this formula and the means of tri-daily determinations of dew-point and wet-bulb temperatures in standard Weather Bureau shelters during 1887 and 1888 as a basis, Russell prepared his well-known evaporation tables for Signal Service Stations in the United States. These tables have been reprinted in several books — not always, however, accompanied by a statement of what the tables really represent.

In deriving his formula, Russell first reduced the evaporation observed with the Piché evaporometer by one-quarter, on the basis of measurements of evaporation from dishes of water placed in the Weather Bureau shelters. He also neglected the effect of wind velocity because by doing so his formula better fitted the observational data. There was considerable variation in the observed wind velocity at the several stations during June, 1888, as shown by Table 17. Moreover, Russell found that at a wind velocity of 5 miles per hour, the evaporation from a Piché was 2.2 times that from one in quiet air; at 10 miles 3.8 times; and at a wind velocity of 15 miles per hour, it was 4.9

times that in quiet air. The wind velocity measured with an anemometer set up inside of a standard shelter at Washington, D. C., for eight days, gave a value of 3.48 miles an hour, which was only 52 per cent of the velocity outside.

In deriving his formula, Russell also increased the observed evaporation in proportion to the relation of 30 to the observed barometric pressure, that is, the observed evaporation at Denver, for example, where the barometer read 24.7 inches was multiplied by $\frac{30.0}{24.7}$ or 1.21 before determining the constants of the equation.

In comparing evaporation from a Piché with evaporation from a reservoir, it is necessary to take account of the fact stated by Russell in the Monthly Weather Review* that:

> "In the case of the Piché evaporometer the temperature of the evaporating water is strictly that of a wet-bulb thermometer exposed at the same place."

The Piché evaporometer observations represent the evaporation at an average wind velocity at the instrument of approximately $3\frac{1}{2}$ miles per hour.

On the other hand, as stated by Russell:

> "The effect of the high exposure of the shelters is to make the figures too great, the wind action being far greater at the height of the shelters than at the level of the ground. The evaporation taking place from a small paper disk, as in the results obtained from the Piché instrument, has a tendency to be too small, as the determining temperature of evaporation is that of a wet-bulb thermometer exposed under similar circumstances. In the case of a body of water the determining temperature of evaporation is nearly that of the average temperature of the air."

Comparison of Evaporation Formulas. — Figs. 142 and 143 show graphically the relative evaporation given by Bigelow's and Russell's formulas, and by the Dalton law, using the au-

* September, 1888, p. 237.

thor's wind factor. In order to permit a better comparison of the three formulas, Fig. 142 was drawn to show the relation between monthly evaporation and monthly mean temperature for constant relative humidities of 50 and 70 per cent and Fig. 143 to show the relation between monthly evaporation and monthly mean relative humidity for constant temperatures of 50 and 77 degrees Fahrenheit. A constant wind velocity of 15 kilometers or 9.3 miles per hour was assumed for all conditions of temperature and humidity. Air and water temperatures were assumed uniform except in the case of Russell's formula, which is based on wet-bulb thermometer temperatures for the water and which gives an evaporation loss equal to three-quarters of that from a Piché.

These diagrams show outstanding differences between the three formulas. On the whole, Russell's formula gives smaller evaporation losses than the other two. As no allowance is made in his formula for wind effect, the values would have been relatively greater if a lower wind velocity had been used in the other two formulas. Bigelow's formula gives very high losses for relative humidities greater than 80 per cent and less than 25 per cent. An evaporation of nearly five inches per month at a temperature of 77 degrees, even though the relative humidity is 100 per cent, seems clearly impossible, unless air and water are not at the same temperature. Similarly, the nearly constant rate of evaporation, with great changes in relative humidity near 100 per cent and the rapidly increasing rate of evaporation at low relative humidities, approaching infinity at zero, do not appear reasonable. Whenever the water temperature is higher than the air temperature, evaporation will not be zero even when the relative humidity is 100 per cent and Bigelow's comments* relative to a continuation " sometimes to a surprising amount " of the evaporation loss from pans, in California and in Maine, during dense fogs, do not prove the Dalton law incorrect, by any means, as the air during a fog is invariably cooler than the water.

* Bulletin No. 2, Argentine Meteorological Office, p. 35.

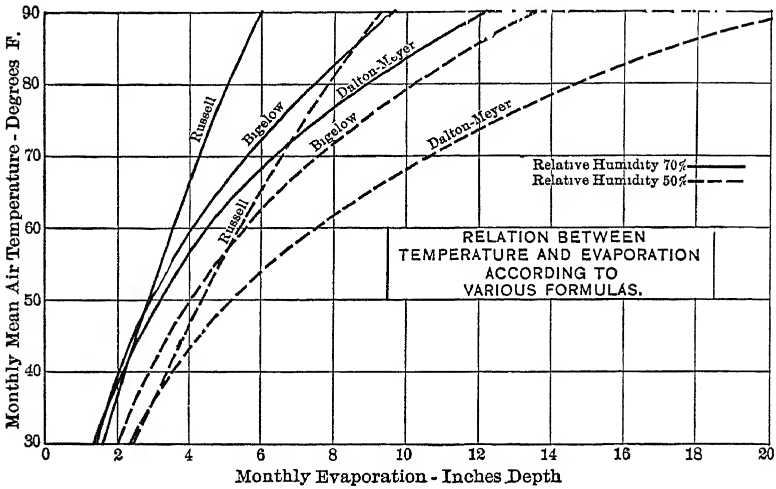


FIG. 142.

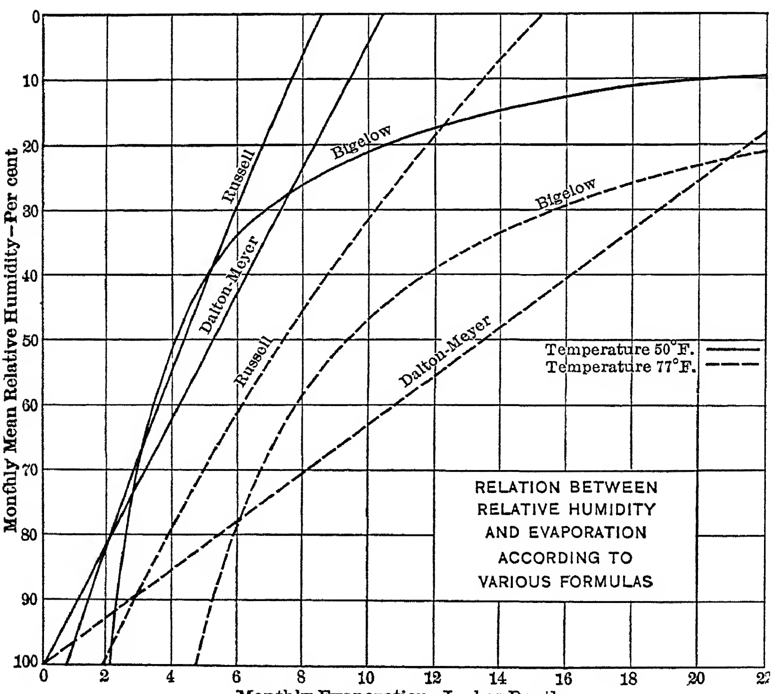


FIG. 143.

In presenting observational data in support of his formula, Bigelow makes an effort to attribute the discrepancy between observed and computed evaporation loss to the expansion and contraction of the water in the evaporation pan.*

It is true, of course, that when the temperature rises, the water expands, so that the observed elevation of the water surface during periods of rising temperature is greater, and, consequently, the observed evaporation loss less than the true loss and *vice versa* during periods of falling temperature. These discrepancies, however, are not at all comparable with most of the discrepancies shown in Bigelow's Table 5, representative samples of which are shown in Table 18.

The data in Bigelow's Table 5, show 18 variations at 2 P.M. in the right direction and 22 in the wrong. Of the 10 P.M. data, there are 19 variations in the right direction and 21 in the wrong.

It is apparent from Table 18 that the evaporation computed by means of Bigelow's formula frequently differs from the observed evaporation for four-hour periods by 15 to 20 per cent.

TABLE 18. — RATIO OF OBSERVED TO COMPUTED FOUR-HOUR EVAPORATION AT TYPICAL STATIONS, TAKEN FROM BIGELOW'S TABLE NO. 5* AND EXPRESSED IN PER CENT

Station	2 A.M.	6 A.M.	10 A.M.	2 P.M.	6 P.M.	10 P.M.
Birmingham, Alabama	79	89	113	131	110	77
Cincinnati, Ohio	80	89	114	124	101	91
Salton Sea, California, Tower 1, Pan 4	109	91	96	108	100	95
Avalon, N. M.	100	95	72	105	126	103

* Bulletin No. 2, Argentine Meteorological Office, p. 23.

* Some observational data are presented by Bigelow on p. 32 of the Argentine Report in support of the above contention. A numerical quantity (given as +0.0046 but apparently +0.0029) resulting from averaging 10 plus values varying from 0.0000 to +0.0204 and 8 minus values varying from −0.0008 to −0.0141 is set forth as comparing favorably with a theoretically required value of +0.0048. Such divergent observational data can hardly be taken seriously in support of any contention whatsoever.

After a careful study of Bigelow's work, the author has concluded to retain, for the present at least, the old Dalton formula.*

TABLE 19. — CORRECTION FOR SIZE OF EXPOSED EVAPORATION PANS

Size of pan	Relative evaporation		
	Grunsky	Bigelow	Sleight *
2 foot	1 87	1.82	1 30
3 "	1 56		1 25
4 "	1 43	1.44	1 19
6 "	1 30	1 24	1 11
Large water surface	1.00	1.00	1 00

* "Evaporation from the Surfaces of Water and River-bed Materials" by R B Sleight, Journal of Agricultural Research, July, 1917.

Correction for Size of Pan. — There does not appear to be any good reason for making a substantial reduction in evaporation from a large water surface as compared with evaporation from a pan floated in the same body of water, as proposed by Bigelow and others.† Differences between evaporation from large bodies of water and from evaporation pans may be ascribed, mainly, to differences in temperature as the result of the use of too shallow pans and the heating effects of the portion of the pan projecting above the water surface. When deep, fully immersed pans are used, comparable results are obtained. For pans entirely exposed above land or water surfaces, however, a correction should be made. Grunsky‡ has proposed a correction based mainly upon the relation between wetted perimeter and area of pan which agrees reasonably well with Bigelow's observations on exposed or partially immersed pans.

* A comprehensive paper on evaporation, together with extended discussions, appears in Trans. Am. Soc. C. E., 1916, pages 1829 to 2060.

† Charles H. Lee in Trans. Am. Soc. C. E., 1927, p. 340, shows that the temperature of the water in floating evaporation pans is substantially the same as that of the body of water in which the pan is floated.

‡ Grunsky, C. E., Trans. Am. Soc. C. E., 1916, page 1970.

Methods of Measurement. — Measurements of the evaporation from pans of water set in the ground or floated from rafts in large bodies of water have been made in a considerable number of places in the United States and elsewhere. Both square and round pans have been used, although the preferable piece of apparatus would appear to be a strong circular pan, 3 feet in diameter and not less than 18 inches deep, with a sharp-pointed indicator in the center. A common mode of procedure, in measuring evaporation, is to add, each day, an amount of water equal to what evaporated during the previous 24-hour period. The water is usually added by cupfuls representing $\frac{1}{100}$ inch in depth over the surface of the evaporating pan, until the water level is again up to the top of the sharp-pointed index in the center of the pan. A rain gage placed nearby is used as a measure of the precipitation on the evaporation pan for which correction must be made. The use of a circular pan has the advantage of always giving the correct height of water even though the pan may not be level.

By far the best way of making an observational determination of evaporation from a large water surface is to use the floating pan, even though it is often difficult to prevent the splash of water both in and out of the pan as the result of wave action. The use of pans suspended above the water or placed in the soil nearby, usually involves still greater possibilities for error. Fine brass wire netting, coiled into a spiral and placed in the evaporation pan but not permitted to project above the water surface, has been found to produce a very satisfactory baffling effect. The evaporation pan should be bound with heavy straps of iron so as to prevent distortion, particularly at the base where the index is fastened, and should preferably be not less than 3 feet in diameter and not less than 18 inches deep, the water being maintained as high in the dish as wave action permits.

In determining the evaporating power of the atmosphere, botanists are making extensive use of porous-cup atmometers. One of the best types in use is that invented by B. E. Living-

stone, and described by him in the December, 1907, "Plant World," page 271.

Observed Evaporation. — Tables 20 to 25 summarize some of the best records of actual observed evaporation from pans floated in relatively small bodies of water. These records all cover several years' observations.

A complete tabulation of observed evaporation on United States Reclamation Bureau projects appears in a paper by Ivan E. Houk in Trans. Am. Soc. C. E., 1927, page 266. The necessity for considering meteorological phenomena in connection with observed evaporation losses is well illustrated by the diagram on page 285 of Houk's paper.

Bureau of Plant Industry data on evaporation were compiled by Robert E. Horton and published in Monthly Weather Review, October, 1921, page 553.

Weather Bureau records of evaporation were published in pamphlet form in 1909–10 and later in Climatological Data.

The wind velocity as observed at Class A Weather Bureau evaporation stations does not represent free exposure of the land pans to wind action, and unquestionably results in evaporation losses which are substantially lower than free exposure would produce. This fact should be taken into consideration when utilizing such Weather Bureau evaporation data.

TABLE 20. — OBSERVED EVAPORATION AT UNIVERSITY, N. D., 1905–1919, inclusive

TABLE 21. — OBSERVED EVAPORATION AT GRAND RIVER LOCK, WIS., 1905–1913, inclusive

	Table 20		Table 21	
Month	Monthly mean air temperature,* degrees F.	Monthly mean evaporation, inches depth	Monthly mean air temperature, degrees F.	Monthly mean evaporation, inches depth
April	42.2	2.69	45	2.83
May	52.4	4.35	54	4.35
June	63.3	4.94	64	5.52
July	67 6	5.69	68	5.74
August	65.5	4.94	65	4.46
September	56.8	3.63	59	3.45
October	42.6	1.98	48	2.22
November	27.1	0.68†	41†	1.09†

* Mean temperature, 1905 to 1916, at University; 1917 to 1919, at Grand Forks.

† Evaporation for small portion of month estimated.

TABLE 22. — OBSERVED EVAPORATION AT BOSTON, MASSACHUSETTS, 1875–1890 inclusive

TABLE 23. — OBSERVED EVAPORATION AT KINGSBURG, CALIF., Nov., 1881–1885 inclusive

Month	Monthly mean air temperature,* degrees F.	Monthly mean evaporation, inches depth		Monthly mean air temperature,* degrees F	Monthly mean evaporation, inches depth
		1875–1885	1875–1890		
January	27	0 90†	0 96†	45 3	0 77
February	28	1 20†	1.05†	50.2	1.25
March	34	1 80†	1 70†	54 4	2 46
April	44 5	3 10†	2.97†	60.8	2 56
May	58	4.61	4.46	67.4	3.39
June	67	5 86	5.54	74 1	5 80
July	71	6 28	5 98	82 1	7 55
August	69	5 49	5.50	81 0	8 65
September	62	4 09	4.12	73 8	6.48
October	52	2.95	3.16	64 2	4 05
November	40	1.63	2 25	54 6	2 12
December	30	1.20†	1.51	47.0	1 19

* Values taken from curve.

† Values largely estimated.

* Mean temperature 1888 to 1902 at Fresno in same valley 20 miles S. E.

TABLE 24. — OBSERVED EVAPORATION NEAR INDEPENDENCE, CALIF., 1908–1911 inclusive

TABLE 25. — OBSERVED EVAPORATION AT LEE BRIDGE, ENGLAND, 1860–1873 inclusive

Month	Monthly mean air temperature, degrees F.	Monthly mean evaporation, inches depth	Monthly mean air temperature, degrees F.	Monthly mean evaporation, inches depth
January	40 2	1.66	38 5	0.76
February	39.8	2.42	40 8	0.60
March	49.2	4 52	42 5	1.07
April	56.5	6 87	48.1	2.10
May	62 5	8.63	54.2	2.75
June	73.2	10.00	60.2	3.14
July	77.5	9.45	64.0	3.44
August	76.5	8.10	63.3	2.85
September	67.3	6.07	58.4	1.60
October	56.6	3.87	50.6	1.06
November	47.7	2.49	43.9	0.71
December	39.0	1.37	39.5	0.62

The observations at University, N. D., were made by Prof. E. F. Chandler for the U. S. Geological Survey. Those at Grand River Lock, Wisconsin, were made by the U. S. Engineer De-

partment. Both the Grand River Lock and the University, N. D., evaporation stations are on small shallow bodies of water. The mean relative humidity at the North Dakota station is slightly less and the wind velocity slightly greater than at the Wisconsin station.

The observations at Boston, Mass., were made by Desmond FitzGerald in the Chestnut Hill reservoir and are fully described by him in Trans. Am. Soc. C. E., Vol. XV, p. 581. Those at Mt. Hope, N. Y. were made by the City Engineer's Office of Rochester, New York.

The observations at Kingsburg, Calif., were made by C. E. Grunsky under the direction of the State Engineer of California. Those at Lee Bridge near London, England, were made by Chas. Greaves and are described in Minutes of Proceedings, Inst. C. E., Vol. XLV, p. 19.

In discussing the Kingsburg observations, Grunsky states that the values are probably somewhat small on account of protection which the pan derived from high banks and a fringe of low trees at a nearby bridge, and also that the temperature of the river water was probably less than that which would have prevailed in an open body of water. Comparison of the observations with other data also indicates that the evaporation is lower than would be expected for the given air temperatures, and that spring evaporation is less for the same temperature than fall evaporation. This is undoubtedly due to the fact that Kings River, on which the observations were taken, is a snow-fed stream.

The observations near Independence, Calif., were made by Chas. H. Lee of the Department of Public Works, Los Angeles, in coöperation with the U. S. Geological Survey and the State of California. The full results are published in Water Supply Paper No. 294.

The data presented in Tables 20 to 25 have been shown graphically in Figs. 144 to 148. The greater evaporation for the same air temperature during the spring than during the

fall results from the generally lower relative humidity and the higher wind velocity at a time when the temperature is rising. Apparently the capacity of the air for moisture is increased at a more rapid rate than evaporation from land and water areas can meet; consequently, the moisture content drops and the rate of evaporation increases. In the case of deep bodies of water the water temperature lags behind the air temperature and the spring evaporation, for the same air temperature, is less than the fall evaporation.

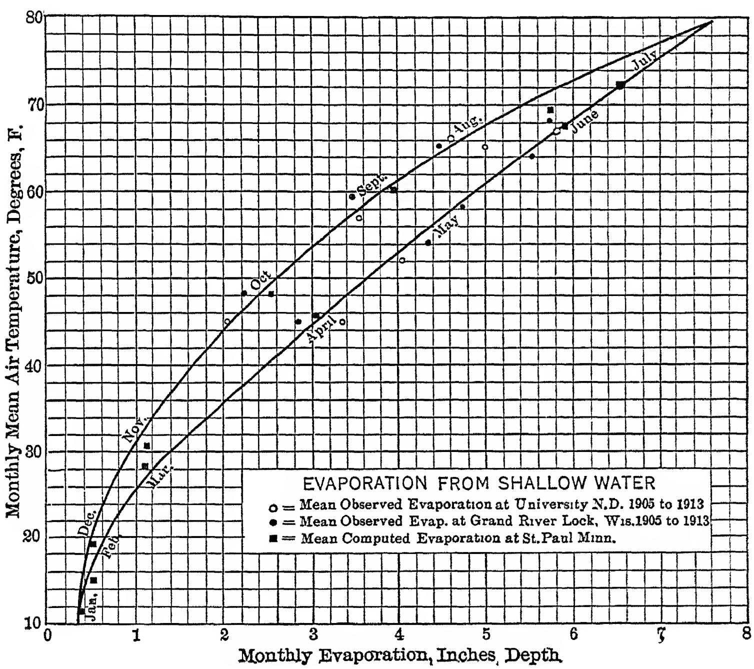


FIG. 144.

The monthly mean rate of evaporation from shallow water at St. Paul, Minn., and Mount Hope, N. Y., computed by means of the Dalton Law, using the author's wind factor, together with the necessary observed meteorological phenomena, is given in Tables 26 and 27.

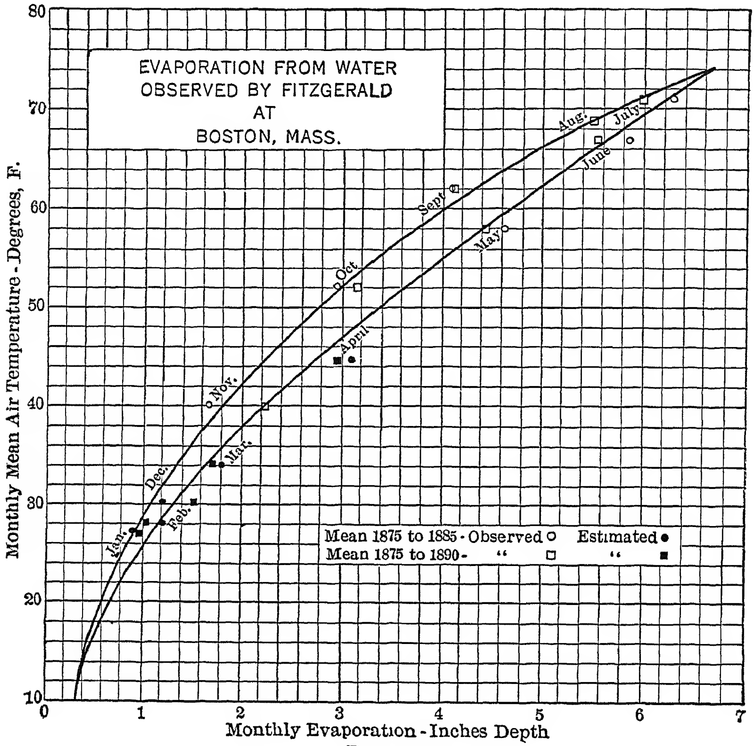


FIG. 145.

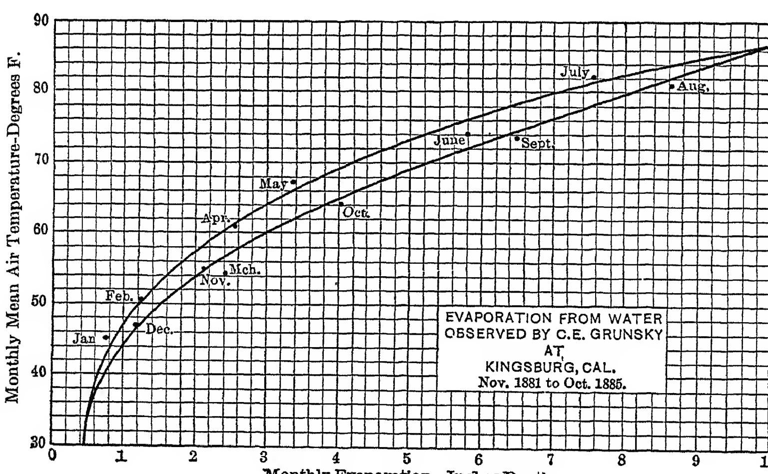


FIG. 146.

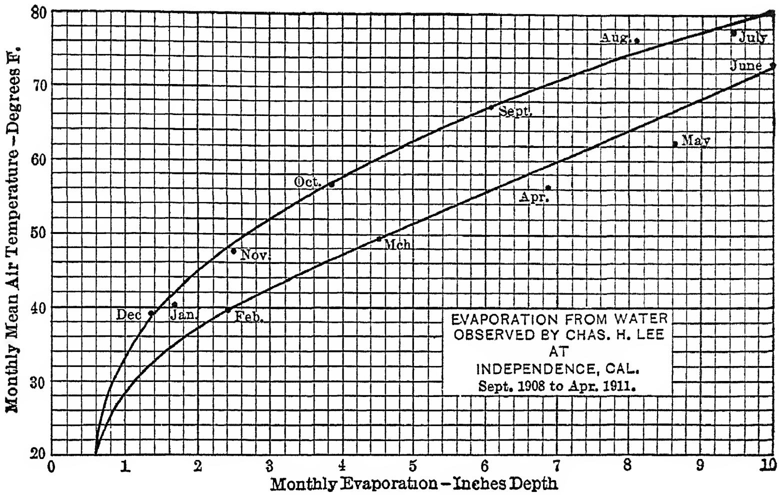


FIG. 147.

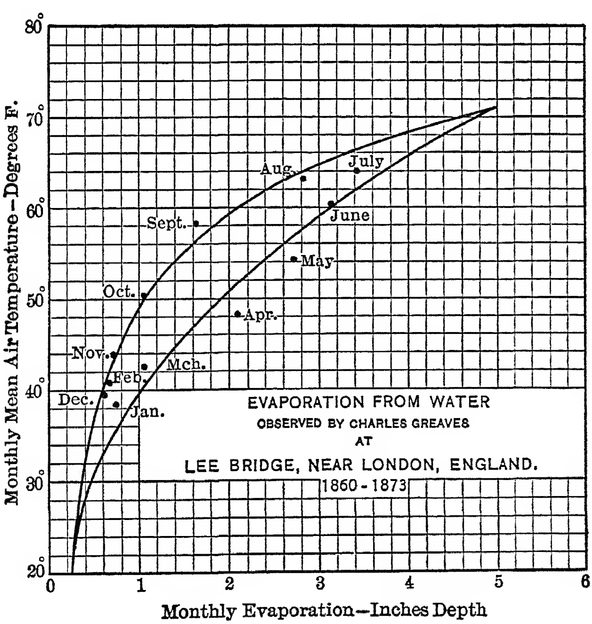


FIG. 148.

TABLE 26. — COMPUTED EVAPORATION AT ST. PAUL, MINN.

Month	Temperature *	Maximum vapor pressure — in. Hg.	Relative humidity, per cent		Difference in vapor pressure	Wind velocity in miles per hour §	Precipitation ‖	Computed evaporation, in inches
			Mean of 8 A.M. and 8 P.M. †	Mean. ‡				
January.........	11.6	0 069	80	81	0 013	7 8	0 90	0 35
February..........	15.0	0 081	79	79	0 017	8 3	0 84	0 47
March.............	28 2	0 151	74	75	0 038	8 8	1 60	1 07
April.............	45 7	0 306	65	66	0 104	9 3	2 33	3 02
May..............	58 2	0 485	64	65	0.170	8 7	3 12	4 76
June..............	67 4	0 670	68	67	0.221	7.7	4 41	5 88
July..............	72 1	0 786	66	¶67 5	0.255	7.1	3 40	6 55
August............	69.5	0.720	69	69	0.223	7.1	3 46	5 72
September.........	60 3	0.523	72	72	0.146	8 0	3 42	3 94
October..........	48 1	0 335	72	73	0 091	8 5	2 34	2 53
November........ ...	30 9	0 171	75	76	0.041	8.1	1 30	1 11
December........	19 3	0 099	79	81	0 019	7 8	1 06	0.51
Annual	43.9	....	72	..	. .	.....	28.68	.....

* Mean of 43 years, 1871 to 1913, inclusive.
† Mean of 24 years, 1888 to 1911, inclusive.
‡ As modified by Minneapolis records.
§ Mean of 36 years, 1873 to 1908, inclusive.
‖ Mean of 43 years, 1871 to 1913, inclusive.
¶ As modified by Minneapolis, Moorhead, and LaCrosse records.

TABLE 27. — COMPUTED AND OBSERVED EVAPORATION AT MT. HOPE, N. Y.

Month	Temperature		Relative humidity	Maximum vapor pressure		Observed vapor pressure in air	Difference in vapor pressure		Wind velocity *	Precipitation	Computed evaporation	Observed evaporation
	Air, in shade	Water, in tub		Water temperature	Air temperature		Air temperature	Water temperature				
Jan.....	24.8	32.5	78.0	0.183	0.129	0.101	0.028	0.082	10.0	1.83	1.21	1.27
Feb....	23.3	32.3	77.9	0.182	0.120	0 092	0.028	0 090	10.9	1.49	1.26	1.26
Mar....	34.1	35.8	73.9	0.209	0.196	0 145	0.051	0.064	9.8	1.96	1.63	2.35
Apr.....	46.7	46.6	68.3	0.317	0.318	0.217	0.101	0.100	8.8	2.21	2.82	2.97
May....	60.1	59.0	68.1	0.499	0.519	0.354	0 165	0.145	7.8	2.69	3.88	3 64
June....	70.5	68.2	68.1	0.689	0.744	0 507	0 237	0.182	7.2	2.47	4.70	4.40
July....	74.7	72.8	68 8	0.799	0.858	0 590	0.268	0.209	7.2	3.70	5.40	5.11
Aug. ..	72.1	71.3	71.3	0.765	0 786	0.560	0.226	0.205	6.5	2.91	5.08	4.73
Sept....	65.7	65.6	74.6	0.629	0.631	0 471	0.160	0.158	7.2	2.44	4.08	3.63
Oct.....	53.1	53.8	75 2	0.414	0 404	0 304	0.100	0.110	7.7	2.37	2.73	2.65
Nov....	39.9	42.5	76.6	0 271	0.246	0 188	0 058	0.083	8.9	1.97	1.80	1.70
Dec.....	28.9	34.3	77.9	0.197	0.156	0.122	0.034	0.075	9.5	1.74	1.28	1.56
Annual.	49.5	51.2	73.2	.....	.....	.....	.....	.....	....	27.77	....	....

* Wind velocity according to U. S. Weather Bureau at Rochester, N. Y., 1895 to 1906.

Temperature is given in °F.; relative humidity in per cent; vapor pressure in inches Hg.; wind velocity in miles per hr.; and evaporation in inches depth.

In computing the evaporation at Mount Hope for January, February, March, and October, November, and December, the author used the difference between the maximum vapor pressure corresponding to the water temperature and a vapor pressure for the air above the water, based on the observed relative humidity and the water temperature.

From April to September, inclusive, the evaporation was computed by taking the difference between the maximum vapor pressure corresponding to the water temperature, and the actual vapor pressure in the air as determined from the air temperature and the observed relative humidity.

During the winter months, the water in the floating tubs (10-inch fiber pails) was at a surprisingly high temperature, presumably due to the pumping of water into the reservoir in which the tubs were floating. It is assumed, therefore, that the layer of air immediately above the water surface was heated to nearly water temperature, and that the most probable value of actual vapor pressure, for use in the formula, would be secured by applying the relative humidity to the maximum vapor pressure at the water temperature rather than at the air temperature observed some distance above the water surface.

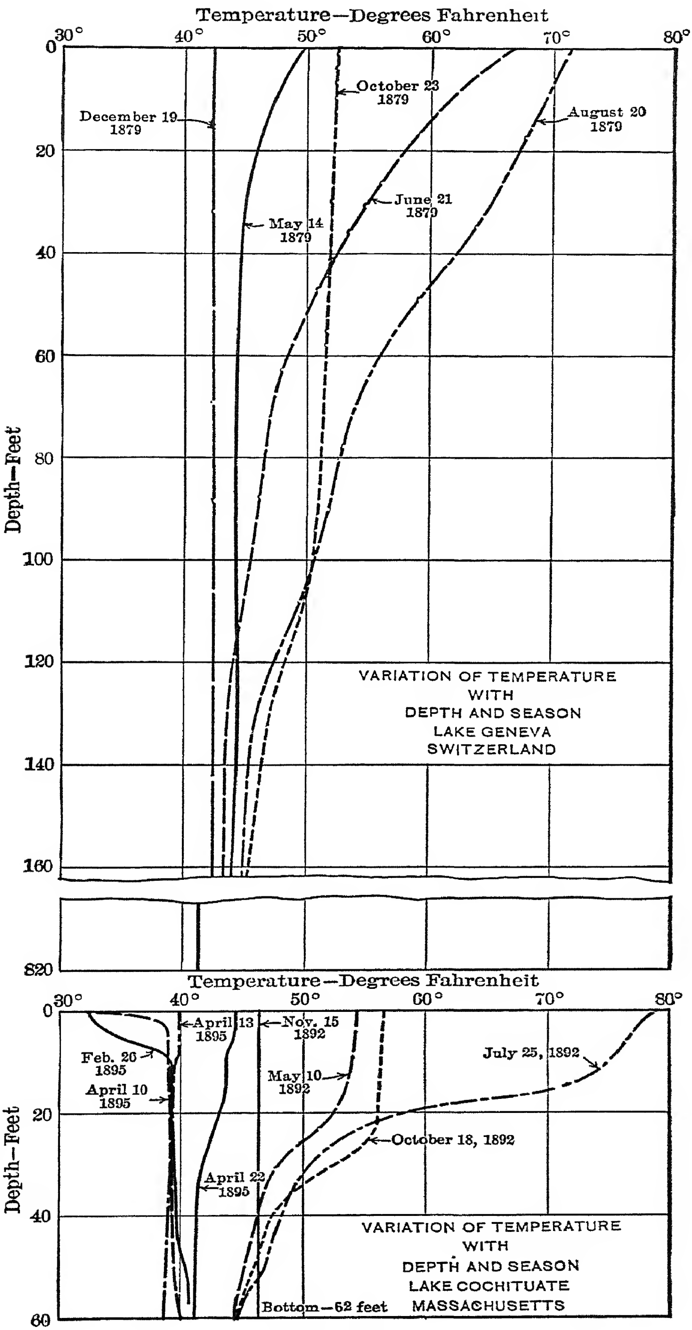
The computed evaporation for St. Paul, Minn., is also shown in Fig. 144, and indicates satisfactory correspondence with actual evaporation observed under similar conditions.

A study of observed evaporation losses from relatively shallow water in comparison with computed losses leads to the conclusion that substantially correct values can be deduced from observed meteorological phenomena without resorting to actual measurements. The temperature of relatively shallow bodies of water follows the air temperature quite closely. Air temperature is being observed at several thousand stations in the United States, and relative humidity and wind velocity are being observed at about 200 stations. Reasonably accurate base data are, therefore, available for use in computing evaporation losses.

Evaporation from Deep Water. — The temperature of large deep bodies of water varies considerably from that of the air. In general, the mean annual water temperature is slightly higher than the air temperature. The extent to which the temperature of lakes varies from the air temperature depends, primarily, upon their depth. In summer, the sun's rays with the aid of currents set up by waves, warm the water of deep lakes to depths of about 150 feet. Below this depth, however, the temperature remains substantially uniform, at a little above the mean annual air temperature, throughout the year. The temperature of the water near the bottom of deep lakes in northern latitudes usually remains very close to the temperature of maximum density.

The variation, with depth and season, of the temperature of Lake Geneva, Switzerland, and Lake Cochituate, Mass., is graphically shown in Fig. 149. Lake Cochituate freezes over, whereas Lake Geneva remains open the year around. After the entire body of water in the former lake has reached the temperature of maximum density, *i.e.*, 39.2° F., the surface water cools and, becoming lighter, remains at the surface until ice forms. With increasing cold, the ice temperature continues to drop and more and more of the layer of water immediately below the ice cover cools down to between 32 degrees and 39.2 degrees. From a few feet below the ice to the bottom of the lake the temperature remains at about the point of maximum density. As soon as the ice breaks up, in spring, the entire body of water soon attains uniform temperature, making it very susceptible to circulating currents set up by air movement over its surface. As the heat received from the sun increases, the surface water heats more rapidly than the deeper layers and, being lighter, remains at the top. The result is that by the end of mid-summer, the surface of the water usually has at least as high a temperature as the air.

During the season of falling temperature the water remains continually warmer than the air, because, as the surface water



Temperature—Degrees Fahrenheit
30°
40°
50°
60°
70°
80°
0
20
40
60
80
100
120
140
160
820
Depth—Feet
October 23
1879
December 19
1879
August 20
1879
June 21
1879
May 14
1879
VARIATION OF TEMPERATURE
WITH
DEPTH AND SEASON
LAKE GENEVA
SWITZERLAND
Temperature—Degrees Fahrenheit
30°
40°
50°
60°
70°
80°
0
20
40
60
Depth—Feet
April 13
1895
Nov. 15
1892
Feb. 26
1895
July 25, 1892
May 10
1892
April 10
1895
October 18, 1892
April 22
1895
VARIATION OF TEMPERATURE
WITH
DEPTH AND SEASON
LAKE COCHITUATE
MASSACHUSETTS
Bottom—62 feet

FIG. 149.

cools, it becomes heavier and sinks and is replaced by warmer water from below. The circulation thus set up extends deeper and deeper. Cooling proceeds throughout a layer of increasing thickness, eventually reaching the bottom of the lake or at least to a depth of about 150 feet below the surface. If cooling continues after the entire body of water has reached the point of maximum density, the surface temperature is rapidly reduced and the lake freezes over.

The currents set up in spring and fall by the change in the temperature of relatively deep bodies of water are of considerable importance in connection with public water supplies on account of their effect on the character of the water.

The temperatures determining evaporation from the lake surface are, of course, the surface water temperatures, but these, it will be noted from what has been said above, are intimately related to the temperature of the entire body of water, and this depends largely upon its depth. The greater the depth of a lake the greater the excess of fall evaporation from its surface over spring evaporation, at the same temperature.

When reasonably complete records of both air and surface water temperatures, in addition to records of relative humidity and wind velocity are at hand, the evaporation from deep water can be computed directly from the observed data by means of the evaporation formula. Usually, however, no such observational data are available.

In order to meet the need for a measure of evaporation from relatively deep bodies of water, and applicable at least to average conditions, the author has constructed the curve of Fig. 150, on the basis of the available observational data and the known general relationship between air and water temperatures. This curve, of course, is intended merely to represent an average measure which may be applied when specific data are not available.

Fig. 151 shows the evaporation loss from the Lake of the Woods as observed by the Manitoba Hydrographic Survey

between 1913 and 1915.* This lake has an area of about 1500 square miles and is about 100 feet deep in places at its northern extremity, but only about 25 feet deep throughout the main

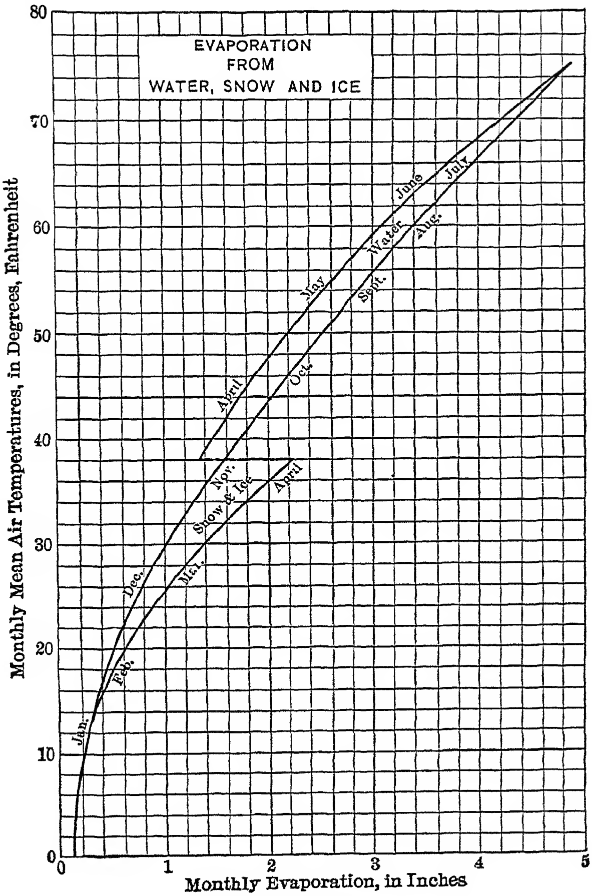
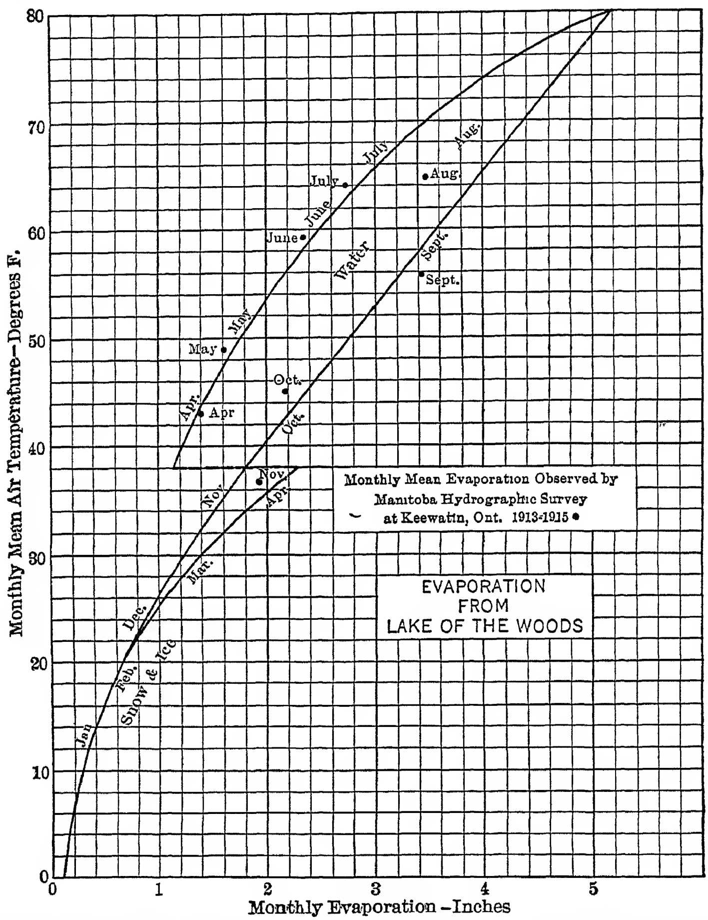


FIG. 150.

southern portion. The water temperature at the northern end, at Keewatin, Ontario, where the measurements were made, lagged considerably behind the air temperature, resulting in

* Observations continued to 1925 do not warrant any material modification of this curve although they indicate a possible shift to the left of about one-tenth inch evaporation.

large differences between spring and fall evaporation for the same temperature. This condition is likely to prevail on all northern lakes where the rate of change in air temperature in spring and fall is great.



From Report of Adolph F. Meyer and Arthur V. White, Cons. Engrs. International Joint Commission.

Fig. 151.

Evaporation from Snow and Ice. — Figs. 150 and 151 also give the evaporation from snow and ice. Few observational data are available as a basis for this part of the curve. While lakes remain frozen, the incident solar energy is used, primarily,

in vaporizing the snow and ice cover. This applies equally to land areas covered with snow.

As early as 1826, Schübler called attention to the high rate of evaporation from snow and ice.

Horton* gives some observations of evaporation from snow which check the values indicated by the curve of Fig. 150 very well. A loss of .25 inch was recorded during the nine days from December 26, 1913, to January 4, 1914. The mean maximum temperature during this period was 29.5 degrees, corresponding to a monthly mean temperature of about 24 degrees. The recorded evaporation for nine days corresponds to a monthly evaporation of .83 inch. The curve of Fig. 150 gives .9 inch of evaporation per month at a temperature of 24 degrees. The mean wind velocity during the period covered by Horton's observations was 7.3 miles per hour. The relative humidity recorded by the Weather Bureau for January, 1914, was 78 per cent. These values represent approximately the normal conditions for the Northwest which constitute the basis for the curve of Fig. 150.

Data bearing on the evaporation from snow at high altitudes, when subjected to desert winds, are found on page 118 of Water Supply Paper No. 294.† A rate varying from twice to over ten times the evaporation from water is given. Such high values, however, are not generally applicable. It may be noted, however, that even the author's curves of Fig. 150 indicate that "chinook" winds of high temperature and low relative humidity can produce high rates of evaporation. At 45 degrees, for example, an extension of the curve would give about 3.4 inches evaporation per month from snow and ice surfaces. This is based upon the relative humidity prevailing in the Northwest. During chinooks, the relative humidity drops very low, so that the evaporation would be increased at least 2½ to 3 times. The evaporation from a water surface at 32 degrees under similar

* Horton, R. E., Monthly Weather Review, February, 1914, p. 99.

† See also Monthly Weather Review, July, 1917, p. 363, and U. S. Geological Survey Water Supply Papers 279 and 294.

conditions of humidity would be about $2\frac{1}{2}$ to 3 inches or about one third as much as the evaporation from snow and ice.

The records of the breaking up of the ice on a large number of lakes indicate that comparatively deep bodies of water may be expected to break up in the spring when the monthly mean temperature reaches about 38° F., and freeze up in the fall when the monthly mean temperature reaches about 20° F.

At the time of break-up there is certain to be a very considerable reduction in evaporation, because the incident solar energy, previously used in vaporizing a surface film of water, snow or ice, is absorbed in melting the ice and gradually heating the water to a considerable depth. After mid-summer, the evaporation from deep water, as previously indicated, will be relatively greater than that from shallow water.

Meyer Evaporation Formula. — The writer suggests the following simple formula for use in computing the approximate evaporation loss from small bodies of shallow water.

$$E = 15\,(V - v)\left(1 + \frac{w}{10}\right)$$

E = Evaporation in inches per thirty-day month.

V = Maximum vapor pressure in inches mercury corresponding to monthly mean air temperature observed by weather Bureau at nearby stations.

v = Actual pressure of vapor in air based upon Weather Bureau determinations of monthly mean air temperature and relative humidity at nearby stations.

w = Monthly mean wind velocity in miles per hour as observed by Weather Bureau at nearby stations, about 30 feet above general level of surrounding country or roofs of city buildings.

As suggested on page 234, for computing evaporation from large bodies of deep water, when the necessary meteorological data are available, use:

V = Maximum vapor pressure in inches mercury corresponding to water temperature instead of air temperature.

v = Actual pressure of vapor in air about 30 feet above water surface.

CHAPTER VI

EVAPORATION FROM LAND AREAS

As the evaporation from land areas is usually a far more important factor in the determination of runoff from a given watershed than that from water areas, a clear understanding of the variation of such evaporation from land areas with temperature, season, rainfall, vegetal cover, topography, soil and subsoil, is essential, even though it involves many factors not readily evaluated.

The quantity of water evaporated from land areas depends not only on the rates of loss but also on the length of time during which evaporation can continue, *i.e.*, it depends not only on the rate of evaporation but also on what Horton * has aptly termed the "evaporation opportunity" as determined by the quantity of moisture available.

The Rate of Evaporation

Effect of Temperature. — The most important factor governing the rate of evaporation from land areas is the temperature of the air and of the moisture subject to evaporation.

Immediately following a rainstorm, the rate of loss from land areas approximates the rate of loss from shallow water. If the ground was quite dry the soil temperature is higher than the air temperature and the rate of loss even greater than that from water. As evaporation proceeds and the free moisture on the surface of vegetation and bare earth disappears, the rate of loss gradually becomes lessened. This reduction in the *rate of evaporation* is more rapid at higher than at lower temperatures so that although at first, after a rainstorm, the *rate of evapora-*

* Horton, R. E., Trans. Am. Soc. C. E., Vol. LXXIX, p. 1171.

tion from land varies with temperature, the same as the rate of evaporation from water, it does not follow that the *quantity evaporated* per day or per month is directly proportional to such rate of evaporation.

Although air temperature does not determine the amount of precipitation lost in evaporation from land areas it is nevertheless an important index to the rate. Records of maximum, minimum,

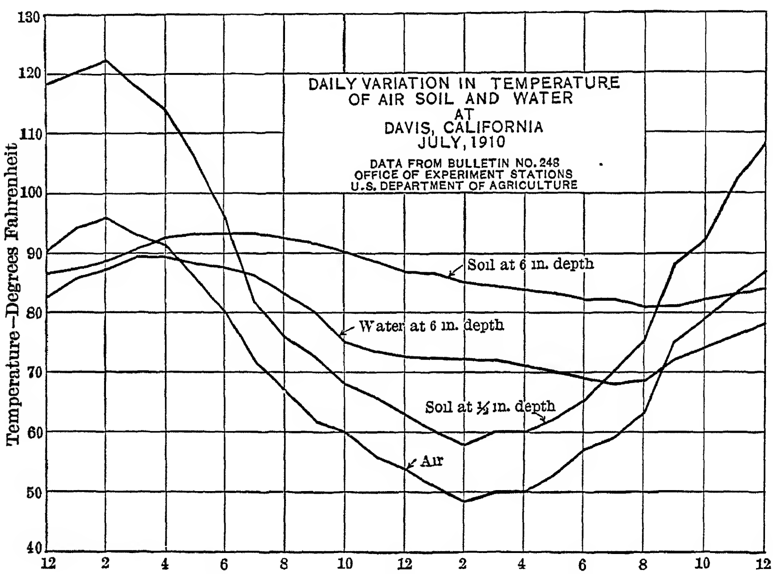


FIG. 152.

and mean daily, monthly, and annual air temperature are available for nearly 6000 Weather Bureau stations in the United States. A determination of the temperature of the moisture that evaporates from land areas must be based on the observed air temperatures. Fig. 152 shows the daily variation in the temperature of the air, water, and dry soil at Davis, California, on July 12 to 13, 1910. The mean temperature of the air for the day was 70.4 degrees. The mean temperature of the dry soil one half inch below the surface was 84.9 degrees

and at six inches below the surface it was 86.8 degrees. The mean temperature of the water at one half inch below the surface was 78.9 degrees decreasing about one degree to six inches depth. The range in air temperature during the day was 47½ degrees while the range in water temperature was only 20 degrees. The range in temperature of the soil at one half inch depth was 64 degrees and at six inches depth 12 degrees. At about 2½ inches below the surface, the range of soil temperature was substantially equal to the range in water temperature.

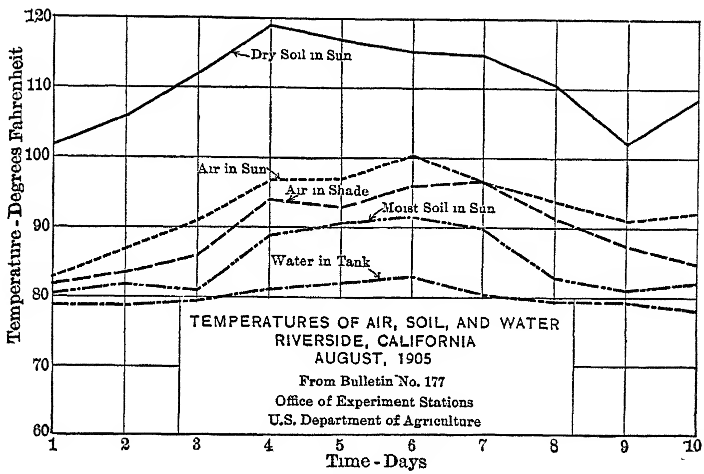


FIG. 153.

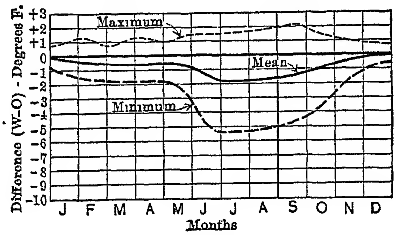
Additional observations showing temperatures of air, soil, and water are shown in Fig. 153.* On the whole, the irrigation investigations indicate that the temperature of dry soil in the sun is higher and the temperature of moist soil is lower, in summer, than that of the overlying air.

Foreign observations on the temperature of the soil and of the air in the forest and in the open field indicate that the mean air temperature in the forest is about two degrees lower in summer, and that the mean annual temperature averages about one degree lower. The difference between the air temperature

* See also "Evaporation from the Surfaces of Water and River-bed Materials" by R. B. Sleight, Journal of Agricultural Research, July, 1917.

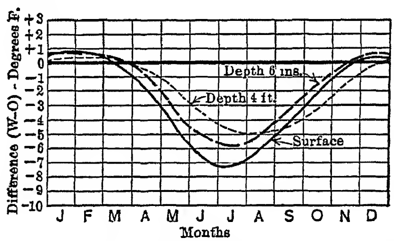
in the forest and in the open is graphically shown in Fig. 154. As the result of this difference in air temperature, a difference is also noticeable in the temperature of the soil in the forest. This is shown in Fig. 155.

From the surface of the ground, the air temperature in the forest rapidly increases, reaching a value a short distance above the tree-tops substantially equal to the air temperature in the open.



Data from Bul. No. 7, Forestry Div., U. S. Dept. of Agr.

FIG. 154. — Difference in Air Temperatures, Woods and Open Fields.



Data from Bul. No. 7, Forestry Div , U. S. Dept. of Agr.

FIG. 155. — Difference in Soil Temperatures, Woods and Open Fields.

In general the daily and monthly mean air temperature may be taken as the best available index to the mean rate of evaporation from land areas.

Effect of Relative Humidity. — The effect of relative humidity on the rate of evaporation from land areas is the same as its effect on the evaporation from water surfaces, namely, the rate of evaporation varies substantially as the saturation deficit. German observations * indicate that the actual moisture content of the air in the forest is only about one per cent greater than

* Reported in Bulletin No. 7, Forestry Division, U. S. Department of Agriculture, p. 102.

in the open, but because of the lower temperature, the relative humidity is from two to three per cent greater than in the open.

Effect of Vegetation. — All forms of vegetation, particularly forests, shade the ground to a certain extent and consequently reduce the rate of evaporation of free moisture.

Transeau * gives the following *relative rates* of evaporation observed at Cold Spring Harbor, Long Island.

	Per cent
Bare sand and gravel slide	100
Open garden plot with low herbaceous vegetation	80 to 100
Upper beach areas	80 to 90
Light forest on gravel soil	50 to 70
Dense forest with abundant undergrowth	35 to 40
Dense ravine forest with abundant herbaceous vegetation	13
Dense swamp forest with abundant undergrowth and water near surface	10
Fresh-water marsh	45

The evaporation was measured with Livingston porous-cup atmometers placed about four inches above the surface of the ground.

The rates given are, of course, merely *relative* and represent rates of evaporation of *free moisture*. According to these observations, the evaporation from the water surface of a fresh-water marsh is reduced to about one half by the presence of the grasses. Open forests appear to effect an equal reduction and dense forests, with abundant undergrowth, reduce the evaporation of free moisture to about one quarter of that in the open. The effect considered here is, of course, the sum total of the effect of vegetation, including reduction in temperature and wind and increase in humidity, but not the effect of vegetation in intercepting rainfall. Practically no watershed, however, has any large area free from all vegetation. The effect of forests in reducing the rate of evaporation of free moisture must be based upon a comparison of evaporation in the forest with evaporation from the ordinary cultivated field, grass land, or brush- and weed-covered watershed.

* Transeau, E. N., Botanical Gazette, April, 1908, p. 218.

German observations * indicate that the evaporation from an evaporation pan in dense woods is 44 per cent and from young trees is 80 per cent of that in the bare, open field.

Considering the rate of evaporation from the bare ground surface at a given mean temperature as 1.0, the rate of evaporation of free moisture from the ground in grain fields may tentatively be taken as .8; for grass land .7; for light forests, brush, and second growth .6; and for dense forests with abundant herbaceous vegetation from .2 to .4.

The Evaporation Opportunity

The opportunity for a given rate of evaporation to continue is determined by the available moisture supply.

Effect of Precipitation. — The available moisture is influenced most largely by the amount, rate, and character of the precipitation that falls on the given watershed. Frequent, light showers that keep the surface soil and the surface of the bare ground and of vegetation moist, permit of the greatest evaporation. Slow, steady rains favor percolation. Torrential rains favor surface runoff. For equal precipitation, then, that which falls as light, frequent showers, provides the greatest opportunity for evaporation.

The character of the precipitation also has an important influence on the evaporation opportunity. During the winter in the Northwest, when most of the precipitation falls as snow and the ground remains covered with snow and ice for several months, the evaporation opportunity on the land area of a watershed is at least equal to that on the water area. If the watershed is covered with a dense coniferous forest, the evaporation opportunity will exceed that for the water area, because the snow lodges on the branches of all evergreen trees and greatly increases the area subject to evaporation loss, besides permitting increased day temperatures in the forest.

* Reported in Bul. No. 7, Forestry Div., U. S. Dep't of Agriculture, p. 102.

Effect of Interception. — During the summer months when the precipitation falls as rain, a greatly varying, but considerable, portion of it is intercepted by trees, shrubs, and other vegetation and re-evaporated without ever reaching the ground. A small portion of the rain caught by the tree tops runs down the trunk.

The quantity of precipitation intercepted by vegetation and re-evaporated, varies largely with the quantity of rain that falls

Courtesy Am. Soc. C. E.

Fig. 156. — Interception of Snowfall by Evergreen Forest.

in a given time. A much larger percentage is lost out of small showers than out of heavy rains. Deciduous trees intercept much more rain during the growing season when in leaf, than in the winter, when the leaves have fallen. Coniferous trees, as above mentioned, intercept large quantities of snow. A typical western evergreen forest with a heavy snowfall lodged on the branches is shown in Fig. 156.

With the exception of Horton's most excellent recent studies* the available data on the subject of interception consist mainly of percentages of precipitation intercepted without reference to actual interception for each rainfall. The average interception at 16 German stations† was 25 per cent; the average of 12 years Swiss observations was 16 per cent. M. Fautrat found 40 per cent intercepted for annual precipitation of about 28 to 30 inches quite uniformly distributed through the year. Riegler found 60 per cent intercepted by spruce and 22 per cent by beech, oak, and maple.

Horton found that forest trees intercepted and re-evaporated about 70 per cent of light rainfalls and about 24 per cent of heavy, long-continued rains. Dense shrubbery intercepted about two-thirds as much and grains and grasses about half as much as trees. When these facts are considered in connection with the reduced rates of evaporation of free moisture from the ground surface in forests, brush-covered lands, and grain fields, as indicated on pages 243 and 244 it would appear that the sum total of evaporation from different parts of the land area does not differ widely. Monthly rainfall interception is not related to the *evaporation from water* in any given month but it is related to the *evaporation from land* as shown in the author's diagram, Fig. 272.

This diagram indicates that when only 1 inch of rain falls in one summer month, as normally distributed into four or five showers of varying amounts, about 80 per cent would be evaporated from the land area; but when 8 inches of rain falls in one month less than 40 per cent would be evaporated.

Since the evaporation of moisture which falls on vegetation necessarily follows about the same laws as the evaporation of moisture which falls on rocks and bare ground surfaces the author has not felt justified in computing interception losses separately

* Rainfall Interception, by Robert E. Horton, Consulting Engineer, in Monthly Weather Review, Sept., 1919, pp. 603–623.

† Reported in Bul. No. 7, Forestry Div., U. S. Dep't of Agriculture, p. 102.

as Horton and others have done. Interception is treated by the author as a form of evaporation from the land area as clearly stated in his discussion of the curve " Evaporation from Land " page 1081, Trans. Am. Soc. C. E., 1915.

Effect of Percolation. — For a given precipitation, the greater the facility for percolation, the less the opportunity for evaporation. Percolation is favored by a slow, steady precipitation, pervious soil, and flat slopes. On some pervious watersheds with relatively steep slopes, however, the surface topography is such as to form numerous, small, wet-weather lakes and ponds that overflow only during exceptional floods. On such watersheds the percolation is always great, and all forms of vegetation reduce percolation by absorbing a large amount of capillary water which would otherwise be held over from one rain to the next, and would permit most of the rainfall absorbed by the surface soil to percolate down to the water-table instead of first replenishing the capillary water used by the plants.

King* found the following rates of percolation through columns of sand and soil having a cross-section of .1 square foot and 14 inches long, when kept covered with 2 inches of water:

In No. 40 † sand,	percolation	at the rate of		301	inches per day.
In No. 100 ‡	"	"	"	39.7	"
In clay loam		"	"	1.6	"

* King, F. H., Nineteenth Annual Report, U. S. Geological Survey.
† No. 40 sand, effective diameter, 0.185 mm.
‡ No. 100 " " " 0.083 mm.

Wollny * found the following rates of percolation in various soils:

TABLE 28. — RATES OF PERCOLATION (Wollny)

Size of soil grain, millimeters	Water sank to the given depth						
	After 5 min	After 10 min	After 15 min.	After 25 min.	After 45 min.	After 65 min	After 120 min.
	cm.	cm.	cm.	cm.	cm.	cm.	cm.
0 01 to 0 071 ..	8 8	12 8	16 2	21 3	30 0	36.7	52 0
0.071 to 0 114	18.0	27 0	37 0	52 5	79.0	103.0	.....
0.114 to 0 195	28 3	48.0	65 0	96.0	.....	.....	......
0 175 to 0.2	45 0	82.0	110 0	.....	....	.....	......
0.25 to 0.50..	84 0	. .	.....	.	. ...	. ...	......
Mixture of various grains	11.0	19 0	24.5	33 2	50.8	65.5	106.0

Wollny's experiments were made with soil of varying grain, placed in tubes 110 cm. deep, the water dropping constantly on top of the soil column.

Although none but the most exceptional watersheds of small area would have a surface covering of coarse sand, yet the difference between clay and sandy soils in facilitating percolation is very marked.

The rate of percolation is also affected by the initial condition of the soil. When the upper layers become nearly air dry to any considerable depth, the pore space becomes so filled with air as to retard, greatly, the entrance of water. This is particularly true of the denser soils, the individual pore spaces of which are relatively small, even though their moisture-holding capacity may exceed that of the coarser sands. The large, deep cracks that form in the clay soils when these are thoroughly sun-baked compensate, in some measure, for the detrimental effects upon porosity of the excessive drying of such soils.

Cultivation, that is, tillage as opposed to cropping, is a great aid to percolation, and unless tilled fields are immediately packed by exceptional, beating rains, cultivation ranks among the most important factors promoting percolation.

* Wollny, E., Experiments reported in Bul. No. 7, U. S. Dep't of Agriculture, Forestry Division.

Fig. 157 shows the effect of cultivation in reducing evaporation from the soil. In this case moisture was supplied by irrigation instead of precipitation, but the effect is the same. It will be noted that about 50 per cent of the 28 day loss occurred in the first three days.

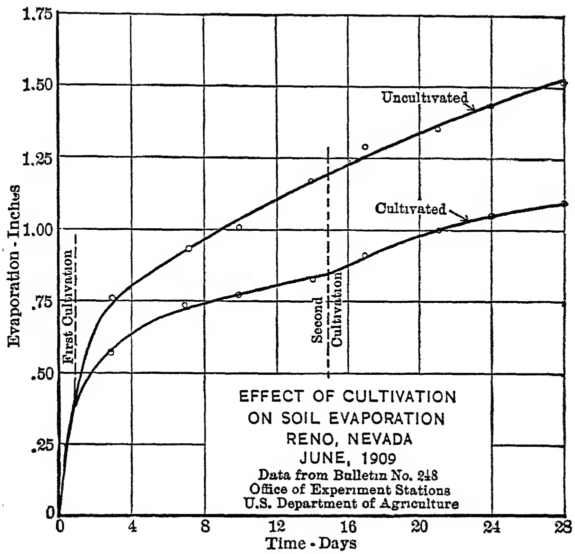


FIG. 157.

Cultivation not only breaks up the sun-baked surface layer so as to reduce surface runoff and aid percolation into the upper layers of soil, but, by forming a mulch, it reduces evaporation. In this way cultivation preserves the capillary water in the soil and permits the additional percolating precipitation to become gravity water and move downward toward the water table where it is usually safe from evaporation.

For any given character of soil, a cultivated watershed which is permitted to lie fallow would yield the best seepage flow. Fall plowing on cultivated watersheds is particularly beneficial, and may result in the storage of a larger quantity of water during the fall, winter, and spring than that used in transpiration during the following growing season.

Depth of Percolation and Rate of Return of Moisture by Capillarity. — Another factor which affects the evaporation opportunity from a given watershed is the moisture-holding capacity of the soil, and the depth to which the percolating waters pass, and also the ability of each particular soil to raise

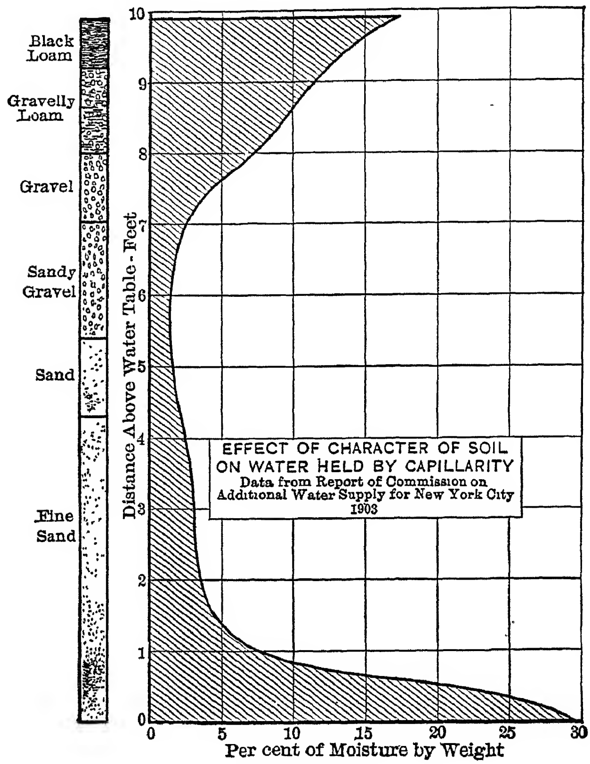


FIG. 158.

water to the surface again by capillary action. The finer the soil and the more humus it contains the greater its capillary power. This is well shown in Fig. 158. Capillary action is also facilitated by the rotted fibers of dead roots, which in some forms of vegetation penetrate to considerable depth.

Hazen * expressed the relationship between size of soil grain

* Hazen, Allen, Report Mass. State Board of Health, 1892, p. 541.

and height to which water will be lifted by capillarity in sufficient quantity to prevent the circulation of air, in the following approximate formula: $h = \frac{1.5}{d^2}$ when h is the lift and d the effective size of soil grain, both in millimeters.

The capillary lift of different soils is also of importance in connection with the life of wooden sub-structures, such as pile foundations, occasionally exposed by low water.

Experimenting on a series of cylinders, each having an area of cross-section of .1 square foot, and filled with a mixture of sand in approximately natural proportions, grains varying in size from No. 100 to No. 20, King * found the following rates of evaporation for capillary lifts varying from 6 to 30 inches. The temperature of the air in the laboratory where the experiment was conducted was about 70° Fahr., and the relative humidity is reported to have been very low.

Capillary lift, in inches above ground-water table	Evaporation, in inches per month
6	3.42
12	3.34
18	2.39
24	1.04
30	0.58

It is worthy of note that the maximum evaporation given in the above tabulation is only about one half of what might be expected from a free water surface under the conditions of temperature and humidity stated. It is probable that if evaporation had been accelerated, capillarity would have shown itself equal to raising the moisture to the surface at a more rapid rate than that found by the experiment for capillary lifts of only a few inches.

The rates of evaporation given for a capillary lift of 30 inches indicate that when the water-table for the particular soil

* King, F. H., 19th Annual Report, U. S. Geological Survey.

used in King's experiments drops to more than 4 or 5 feet below the surface of the ground, evaporation is reduced to a very small quantity.

Lee * states that the capillary lift is practically limited to four feet in coarse sandy soil, and to eight feet in fine sandy or clayey soil.

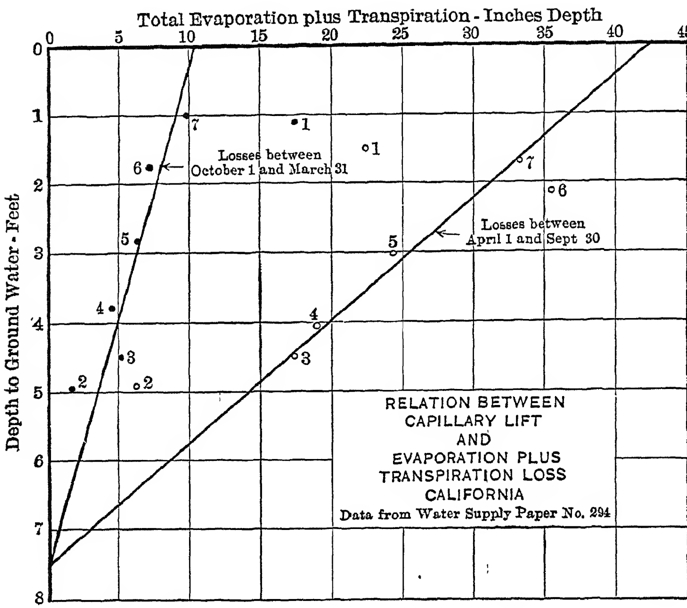


FIG. 159.

The results of some of Lee's observations on evaporation and transpiration losses from the Owen's Valley, California, soils are summarized in the curves of Fig. 159. The deviation of the observed losses from Tanks Nos. 1, 2, and 6 from the straight line relationship shown by the other observations results primarily from the fact that the surface of Tank No. 1 consisted of bare sand, No. 2 had but scattered growth of salt grass, and No. 6 had a vigorous growth of grass.

* Lee, Charles H., Trans. Am. Soc. C. E., Vol. LXXVIII, p. 148, and U. S. Geological Survey, Water Supply Paper No. 294, p. 59. See also discussion of capillary siphoning of water through soil in Bul. 835, U. S. Dep't of Agriculture.

McGee * states: "While the effectiveness of capillary movement varies with the texture and structure of soil and subsoil and underlying rock, it may be said broadly that under average conditions capillarity acts freely to four or five feet in depth, fairly to ten feet, and slowly to thirty or more feet."

Burr, Hering and Freeman concluded from their Long Island studies † that water percolating to eight feet in fine sand and three or four feet in coarse sand will not return.

Slichter ‡ found that while the evaporation from a water surface in Kansas from August 6 to September 3, 1905, was 10.90 inches, the evaporation from cultivated soil with a water table within one foot of the surface was 4.88 inches and from uncultivated soil with the water-table at the same level, 5.83 inches. The evaporation from the soil for a capillary lift of two feet was 2.23 inches and for a capillary lift of three feet the evaporation was reduced to .80 inch.

Professor Whitney § found that certain soils in southern California had such extensive capillary power as to be able to draw sufficient water from a depth of twenty feet or more to mature crops on one inch of rainfall between May and September, while neighboring soils were practically barren.

Extensive capillary action, coupled with excessive evaporation, results in the bringing of large quantities of salts to the surface of the ground and in the formation of what is known as "alkali" soil.

Briggs and Lapham || found that moist sandy soil exerted a capillary lift of 65 inches.

Stewart ¶ found moist, sandy, rich soils to exert capillary lifts of from 45 inches to 70 inches.

* McGee, W. G., 1911 Yearbook of the Department of Agriculture, p. 482.

† Report of the Commission on Additional Water Supply for the City of New York, 1903, p. 756.

‡ Slichter, C. S., Eng. News, July 5, 1906.

§ Whitney, Wilton, Yearbook U. S. Dep't of Agriculture, 1897, p. 432.

|| Bulletin No. 19, Bureau of Water, U. S. Dep't of Agriculture, 1902, p. 26.

¶ Stewart, J. B., Thesis "Capillary Rise of Water in Soils," Michigan, Agricultural College, 1901.

Not only the extent of the capillary lift, however, but also the rate of movement of water for given capillary lifts is important. Fine, clayey soils exert a great capillary lift, but the interstices are so small as to offer such great resistance to flow that the maximum rate of movement of water is relatively small. For low capillary lifts, sandy soils will supply much more water at the surface of the ground for evaporation and transpiration than clayey soils. On the other hand, clayey soils will supply moisture at the surface even when the water table has dropped far out of reach of sandy soils. Soils containing considerable humus not only exert a strong capillary lift but permit rapid movement of the water through the pore space.

The depth to the water table, then, is an important factor in determining the evaporation opportunity.

Depth of Water-table. — The average depth of the water-table in central United States is well shown by Dr. McGee's * investigations on the depth to the water surface in wells. On the basis of reports received for 7498 wells, it appears that the average depth to the water surface,— which is probably two or three feet below the water-table of the surrounding country — varies from 17.9 feet in Indiana to 22.6 feet in Wisconsin, averaging 22.2 feet for the entire central portion of the United States. About half of the wells reported no change in elevation of the water surface within the memory of the reporter. The average of those reporting a change during the period within the memory of the reporter, which averaged about 25 years, indicated a lowering in the water-table, varying from about one foot in Missouri, to nearly four feet in Wisconsin and Minnesota. Inasmuch as the data compiled by Dr. McGee appear to be based merely on *testimony* as to changes and are not the result of observations regularly reported during the course of 25 years, it would appear that the water surface in the wells must have remained substantially stationary. An increase

* McGee, W. J., 1911 Yearbook of the Dep't of Agriculture, pp. 479 to 490.

in settlement results almost invariably in the improvement of water supplies. This usually means drilled wells and often sufficient pumping to considerably lower the water-table immediately adjacent to the wells. It is doubtful whether the data presented by Dr. McGee warrant the conclusion that the water-table throughout the Mississippi Valley has been materially lowered during the past 25 years.

Effect of Vegetation. — Vegetation affects the evaporation opportunity in several ways. By using some of the capillary water, plants reduce the evaporation opportunity, so far as the soil is concerned, but through interception of precipitation, as previously explained, they increase the evaporation opportunity.

In so far as plants use water for their growth and in this way keep the moisture content of the soil lower than it would otherwise be, they reduce percolation. In so far as all forms of vegetation present some obstruction to the flow of water over the surface of the ground plants aid percolation. Leaf mold in the forest presents a pervious surface to precipitation. A layer of undecayed leaves, on the other hand, presents an almost impervious surface. Leaf mold has great moisture holding capacity. In consequence, the surface soil in the forest is usually quite moist and the evaporation opportunity is increased, although the rate of evaporation, as previously stated, is considerably reduced by the shade of the forest. Ample moisture supply in the surface soil fosters the growth of luxuriant herbaceous vegetation with the consequent increased water consumption in transpiration, except in dense coniferous forests and those deciduous forests of tall dense timber that prevent the entrance of sufficient light to support small vegetation.

Wollny found that a grass cover reduced percolation below the root level to practically half of that permitted by bare soil.

Ebermayer found that young beech and spruce trees reduced the amount of water found to percolate below the four-foot level. In his experiments, only about two inches, out of a total

of 37.6 inches of precipitation, percolated below this level. During the winter, the percolation through the experimental boxes which contained young deciduous trees was substantially equal to that for the boxes which contained bare soil, but during the summer, the percolation was much less for the boxes which contained the trees.

The effects of vegetation on percolation, found by Wollny and Ebermayer, are undoubtedly due to the amount of capillary water used by the plants rather than to any surface effect in obstructing percolation.

Ebermayer found that during summer and fall a loamy, sand soil contained about 20 per cent of moisture in the open, fallow field, as against 15 per cent in the forest at depths of from 16 to 30 inches. More moisture, however, was found in the upper few inches of the forest soil.

In a field in which the water-table was from 5 to $8\frac{1}{2}$ feet below the surface of the ground, and in which alternate strips of land had been planted to corn, King found the plane of saturation depressed materially under the corn. During the succeeding season, corn was planted in the strips which had lain fallow the previous season and the water-table was again found depressed by the vegetation.

The magnitude of the several effects of vegetation on the evaporation opportunity usually depends upon the character of the watershed and the character of the vegetation.

Effect of Drainage. — The principal effect of both tile and open ditch drainage on the evaporation loss from land areas is to reduce the evaporation opportunity. The drainage of land presupposes an excess of moisture on the surface of the ground and in the upper few feet of soil — the layer from which the evaporating water is primarily drawn. By removing both wet-weather and permanent ponds and pools, by lowering the water-table, and by eliminating all gravity water from the upper layers of soil, drainage reduces the opportunity for evaporation losses from land areas.

Other effects of drainage will be considered in discussing stream flow.

Observed Evaporation Losses from Land Areas. — Scientific literature affords few records of actual measured evaporation losses from land areas. Most of the available data do not differentiate between evaporation and transpiration. As these two losses do not vary in the same way with the changing seasons they should be separately considered.

Irrigation Investigations. — Among the best available data on evaporation losses are those published by the U. S. Depart-

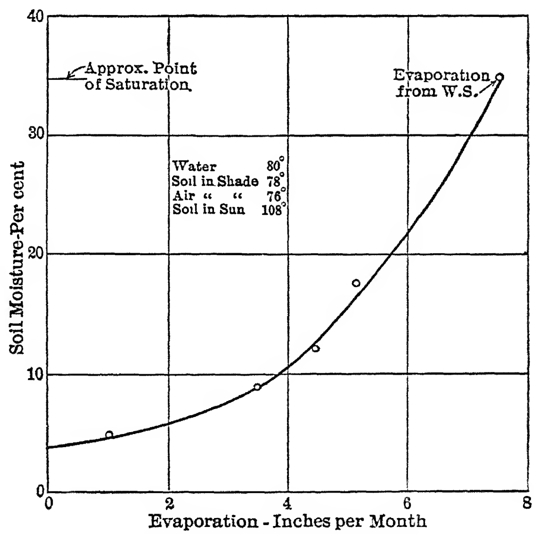


FIG. 160. — Relation between Soil Moisture and Evaporation, California.

ment of Agriculture and similar departments of several states.* Although surface irrigation and precipitation differ in important respects, yet the data gathered in connection with irrigation investigations are of great assistance in gaining an understanding of the factors that influence evaporation from land

* For example: Bulletin 177, Evaporation Losses in Irrigation, and Bulletin 248, Evaporation from Irrigated Soils, Office of Experiment Stations, U. S. Dep't of Agriculture.

areas and the amount of evaporation that occurs under certain conditions.

Fig. 160 shows the relation between the moisture available in the soil and the quantity evaporated.* The soil experimented with was a well-pulverized, sandy loam. The rapid decrease in the rate of evaporation after the percentage of moisture dropped below 10 is significant. When the moisture content of this particular soil dropped below 3.5 per cent of its dry weight, evaporation practically ceased.

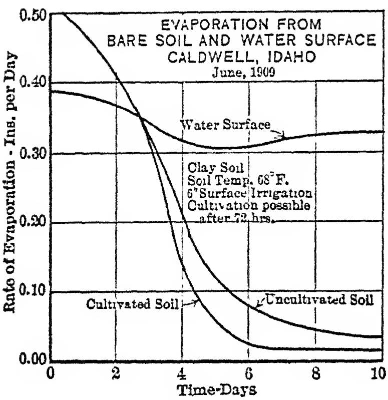


FIG. 161.

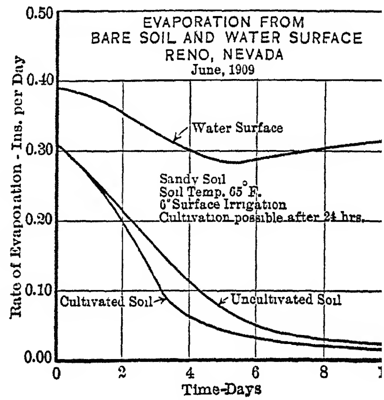


FIG. 162.

Relative Evaporation from Land and Water. — Figs. 161 and 162 show the rates of evaporation from bare soil and from a water surface, in the same locality. The evaporation from the clay soil at Caldwell, Idaho, for about three days following the application of irrigation water, actually exceeded the evaporation from a water surface. This is undoubtedly due to the fact that the irrigation water was held so long at the surface of the clay soil, and the temperature of the soil at the beginning of the experiment was very much higher than the temperature of the water in the evaporation tank. In the case of the sandy soil at Reno, Nevada, the evaporation loss from the soil from

* The data used in constructing this curve were taken from Bulletin No. 177, Office of Experiment Stations, U. S. Dep't of Agriculture.

the very beginning was less than the loss from the water surface. This sandy soil absorbed six inches of surface irrigation in a few hours and was sufficiently dry to permit surface cultivation after 24 hours, whereas the clay soil at Caldwell could not be cultivated until after three days. A significant fact brought out by these diagrams is the fact that about half of the evaporation loss from the soil occurred in the first three days after irrigation. Other records of the office of Experiments Stations point to the same conclusion.

Some of the actual measured evaporation losses from land areas, determined by the U. S. Department of Agriculture in its irrigation investigations, together with such other relevant data as were available, are summarized in Table 29.

Effect of Character of Soils. — The soils used in the experiments at Wenatchee, Reno, Sunnyside, and Caldwell contained substantially the same amount of initial moisture and received practically the same amount of water through surface irrigation and precipitation. The coarser sandy soils at Wenatchee and Reno permitted rapid percolation, as indicated by the high moisture content in the bottom layers of the soil at the end of the experiment. This reduced the moisture content in the upper layers and consequently reduced the subsequent evaporation loss. The clay soil at Caldwell, on the other hand, retarded percolation, as indicated by the fact that it required 20½ hours to absorb six inches of irrigation water, and then permitted an evaporation loss of about one quarter of that from the water surface. The evaporation loss from the Williston gumbo amounted to nearly half that from a water surface, and the Bozeman soil with its great moisture-holding capacity permitted two thirds as much evaporation in 28 days as a water surface in the same locality. The Bozeman soil was of extremely fine texture, and exerted such a great capillary lift that the moisture content at the close of the experiment was substantially uniform throughout.

TABLE 29. — OBSERVED EVAPORATION FROM LAND AREAS

Data from Bulletin No. 248, Office of Experiment Stations, U. S. Dep't of Agriculture, 1912

Station	Duration of test, days	Evaporation, inches depth			Mean temperature, degrees F.			Irrigation water applied	Rainfall, inches	Moisture in soil, per cent				Character of soil
		From water surface	From bare soil	Ratio soil to water	Air	Water	Soil			At beginning of test		At end of test		
										Top soil	Bot. soil	Top soil	Bot. soil	
Wenatchee, Wash.	21	6.12	0.86	0.14	79*			6 in.	Trace	6.0	6.0	6.5	15.5	Sandy loam with some grit.
Reno, Nevada.....	28	8.49	1.51	0.18	56.6		67.9	6 in.	0.39	8.1	9.3	9.2	17.0	Sandy alluvial loam intermixed with sand.
Sunnyside, Wash.	28	(7.25)?	2.47		65.2	70.9	74.3	6 in. in 7 hours	0.00	6.0	6.0	.		Fine and uniform-grained sandy loam.
Caldwell, Idaho	28	9.81	2.42	0.25	72.2	68.4	69.4	6 in. in 20½ hours	0.14	4.6	6.2			Clay loam and clay changing to sandy loam.
Williston, N. Dakota.	21	4.21	1.99	0.47	67.9	69.5	61.1	6 in.	1.26	3.7	3.7	.	...	Sandy gumbo changing to sandy loam.
Bozeman, Montana..	28	4.38	2.92	0.67	64.4	75.0	74.6	5 in. in over 24 hr.	0.99 in light showers	17.8	17.8	22.5	22.5	Silty loam rich in humus, changing to heavy loam.

* Mean maximum temperature.

CHAPTER VII

TRANSPIRATION

Definition. — Transpiration is the process of vaporization of water from the breathing pores, or stomata, of leaf and other vegetable surfaces.

Effect of Temperature. — Clements * states that 95 per cent of the light energy absorbed by the chloroplast of the leaf is converted into heat. Most of this heat is used in the vaporization of the water from the dilute solutions of mineral salts drawn into plants through the root system and used in building up plant tissue. The moisture retained in the plant tissues themselves is an inconsequential factor in the disposal of precipitation.

In discussing evaporation, it was indicated that, other factors remaining constant, the rate of evaporation from shallow water is approximately doubled for every 18 degrees increase in temperature. Van't Hoff and Arrhenius have enunciated the principle that most chemical reactions and physiological processes double in activity for every similar increase in temperature. This law has been found, by experiment, to apply to a number of phases of plant activity. It has, for example, been found to be substantially correct for the rate of fixation of carbon dioxide by plants in sunlight; and, inasmuch as transpiration occurs during the process of carbon dioxide assimilation, when the stomata open in the sunlight, it is reasonable to conclude that the rate of transpiration, in so far as it is dependent on temperature, substantially follows Van't Hoff's law.

In applying this law, however, it is necessary to decide on a temperature at which plant activity begins. Köppen regards all

* Clements, F. E., Plant Physiology and Ecology, p. 85.

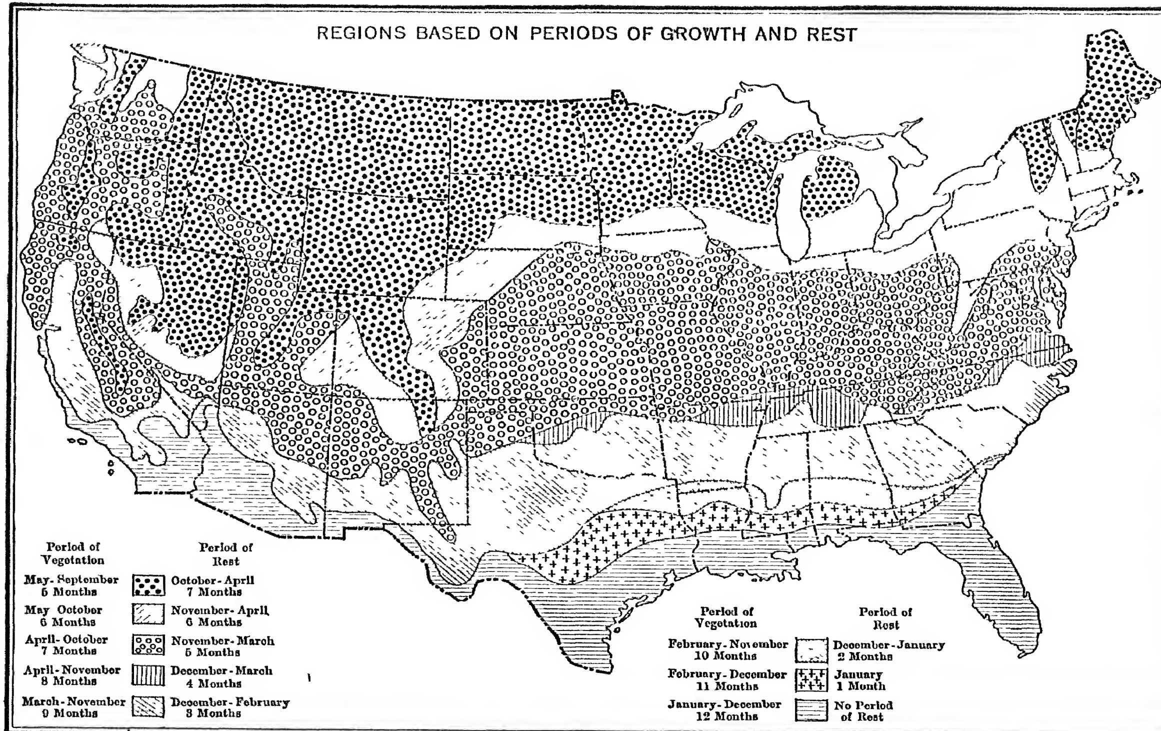


FIG. 163. — Vegetal Regions in the United States Based on Periods of Growth and Rest (after Zon).

monthly mean temperatures less than 48 degrees as included in the period of rest of plants. Other scientists hold that the protoplasmic contents of vegetable cells are inactive while the temperature is below 6° C. (42.8° F.).

Fig. 163 shows the United States divided into different vegetal regions based upon periods of growth and rest as determined by temperature alone, without reference to available moisture.

In temperate latitudes, when there is a lack of precipitation or irrigation, monthly mean temperatures of more than 72 degrees constitute a period of summer rest for most plants. When sufficient moisture is present, they constitute a period of ripening for southern fruits, and, when there is an abundance of moisture, these high temperatures constitute the period of sub-tropical growth.

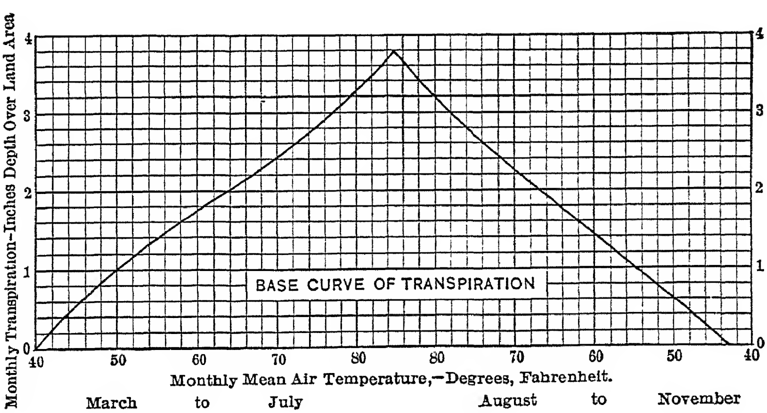


Fig. 164.

Fig. 164 shows the author's base curve of transpiration founded mainly upon the above expressed effect of temperature on transpiration. This curve is used as the basis for estimating changes in monthly transpiration, on a given watershed, with changes in monthly mean air temperature, without reference to available moisture.

Figs. 165 and 166 show the relation between maximum and minimum daily temperatures and the growth of corn. The rate

of growth is approximately doubled for an increase of 15 degrees in temperature.

Botanists agree that every plant has its optimum moisture, temperature, and light conditions under which it makes its best growth. When there is an excess of moisture, crop yields are

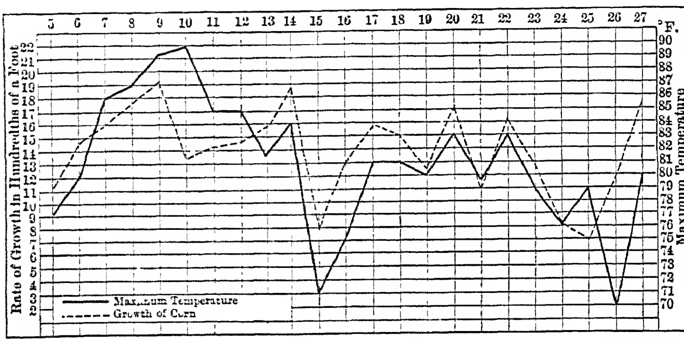


FIG. 165. — Relation between Maximum Temperature and Daily Growth of Corn in Pennsylvania, July 5–27, 1889 (after Smith).

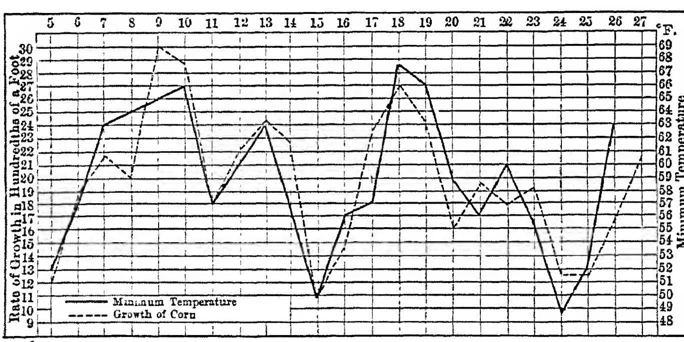


FIG. 166. — Relation between Minimum Temperature and Nocturnal Growth of Corn in Pennsylvania, July 5–27, 1889 (after Smith).

determined largely by temperature. When rainfall is sufficient and the temperature is too low for best growth, sunshine becomes the most important factor. Heat cannot replace sunlight in the growth of vegetation, but sunlight can partly replace heat. When temperature and sunshine are sufficient, crop yields depend mostly on rainfall.

Effect of Humidity. — All the experiments which have been made upon the water requirement of plants, for a given amount of growth, indicate that more water is used, per pound of dry material produced, by plants growing in dry air than by those growing in moist air The experiments of Montgomery and Kiesselbach,* on corn grown in greenhouses, indicate that the amount of water required per pound of dry material produced is proportional to the evaporation from a water surface, which, it has already been shown, is proportional to the saturation deficit of the air. The plants grown in the humid atmosphere (58 per cent relative humidity during daylight hours) produced about 25 per cent more dry matter and used about 12 per cent less water than those which grew in the dry atmosphere (37 per cent relative humidity during the day). From an engineering viewpoint the effect of relative humidity on the total amount of water used, rather than on the water used per pound of dry matter produced, is the effect desired. This, however, does not appear to have been determined. It is probable, however, that the increased growth resulting from increased humidity causes a total water loss in a humid atmosphere about equal to that in a moderately dry atmosphere provided a reasonably sufficient amount of soil moisture is available for the plant to use.

Effect of Wind. — By hastening the removal of vapor from the leaf surfaces from which it is being transpired, air movement results in increased transpiration.

Effect of Light. — Transpiration is practically limited to the daylight hours. In this respect it differs from evaporation, which continues through the night at a rate determined, primarily, by the temperature. This is well shown by Fig. 167 which gives a continuous record of the transpiration of wheat, observed at Akron, Colo., in July 14–15, 1912, and reported in "Journal of Agricultural Research," Vol. 5, No. 3. The loss during the night was about one tenth of the loss during the day, which reached its

* Montgomery, E. G., and Kiesselbach, T. A., Nebraska Agricultural Experiment Station, Bulletin 128, 1912.

maximum at noon. The loss during the night was also substantially uniform.

As the leaves of plants turn toward the sun, it is immaterial what the slope of the ground is,* or what the angle of the sun is during the daylight hours except in so far as the longer path of

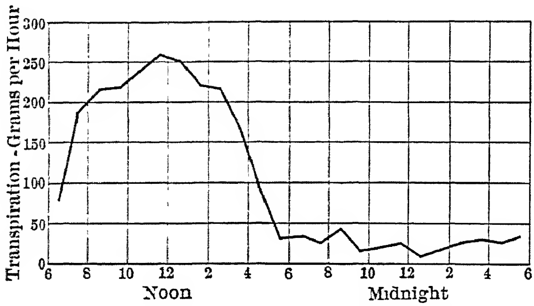


FIG. 167. — Variation of Transpiration of Wheat with Daylight, July 14–15, 1912.

the sun's rays through the atmosphere during the early morning and late afternoon has an effect on the absorption of a part of the sun's energy. The following table shows the proportionate amount of solar radiation reaching the earth for various angular altitudes of the sun, considering the amount reaching the earth with the sun in the zenith as 1.00.

Angle of sun	Relative amount of solar radiation reaching earth
90	1 00
70	0 99
50	0 92
30	0 75
20	0 57
10	0 27
5	0 07

It has been found that the longer heat rays are much more readily absorbed by the water vapor and carbon dioxide of the

* Clements, F. E., Research Methods in Ecology, p. 59.

earth's atmosphere than the shorter light rays. The light rays at the red end of the spectrum are most useful to the plants. William Siemens found, in London in 1879 to 1881, while experimenting on the growth of *Mimosa pudica,* that the red rays are about four times as effective in promoting growth as the white rays and ten times as effective as the blue.

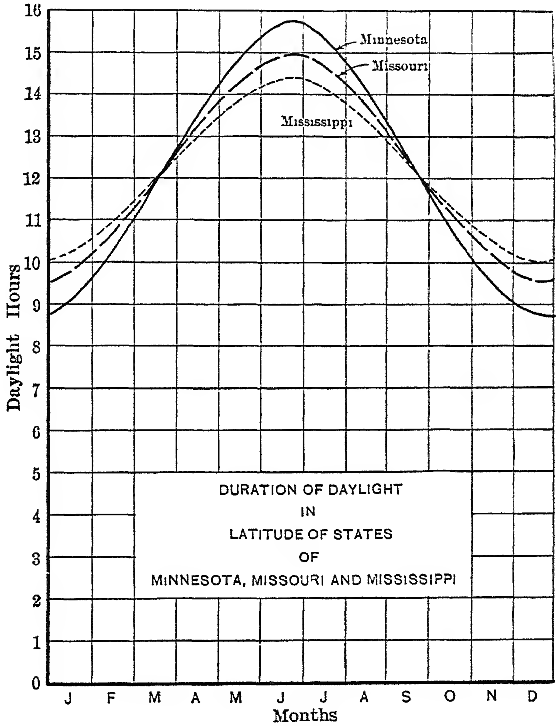


FIG. 168.

The amount of daylight during the growing season greatly affects the growth of plants. The duration of daylight in various latitudes is shown in Fig. 168. It will be noted that in midsummer, Minnesota has about one and one half hours more of daylight each day than Mississippi, besides having a great deal more of twilight.

As transpiration is dependent upon sunlight, shade naturally reduces transpiration. Most experimenters have found that

complete shading reduces transpiration to about one half or one third of that in full sunlight. Hasselbring, experimenting on tobacco plants in Cuba, found that the shade of ordinary cheesecloth reduced the transpiration 30 per cent.

Effect of Soil Moisture. — Most students of the subject of transpiration seem to be agreed that the quantity of water used by plants during the growing season depends mainly on the quantity available within reach of the root system. It has been found that, in any given soil, all forms of vegetation wilt when the moisture content is reduced to a certain percentage. This percentage, however, — known as the "wilting coefficient" — varies greatly for different soils.

The moisture in the soil may, for practical purposes, be divided into two portions, namely, "gravity water" or that portion which will be drawn down into the lower layers of the soil by gravity, and "capillary water" or that portion which is held in place in the soil at an elevation of about 5 feet or more above the water-table by capillary attraction. Of the capillary water, nearly one half is available for plant growth and about three fourths will readily evaporate. Of the remainder, — hygroscopic water — little will evaporate from the soil below the upper few inches in fields, although it may all be readily driven off by heating the soil to a little above 212° F. The relation between character of soil and the amount of capillary water, gravity water, and hygroscopic water which soil may contain is graphically shown in Fig. 169 (a and b).

Fig. 169 (a) is based upon data taken from the Bulletins of the Bureau of Plant Industry, U. S. Department of Agriculture. The moisture-holding capacity of a soil is defined as the percentage of water held in short soil columns one centimeter in height. The moisture equivalent of a soil is the percentage of water which it can retain in opposition to a centrifugal force 1000 times that of gravity. The wilting coefficient is the percentage of water retained in soils when plants growing therein wilt to such an extent as not to recover turgidity upon being placed in saturated air.

The hygroscopic coefficient represents the percentage of water which soil contains when kept in a saturated atmosphere.

The investigations of Briggs and Shantz * indicate that sand can, by capillary attraction, hold an amount of water equal to

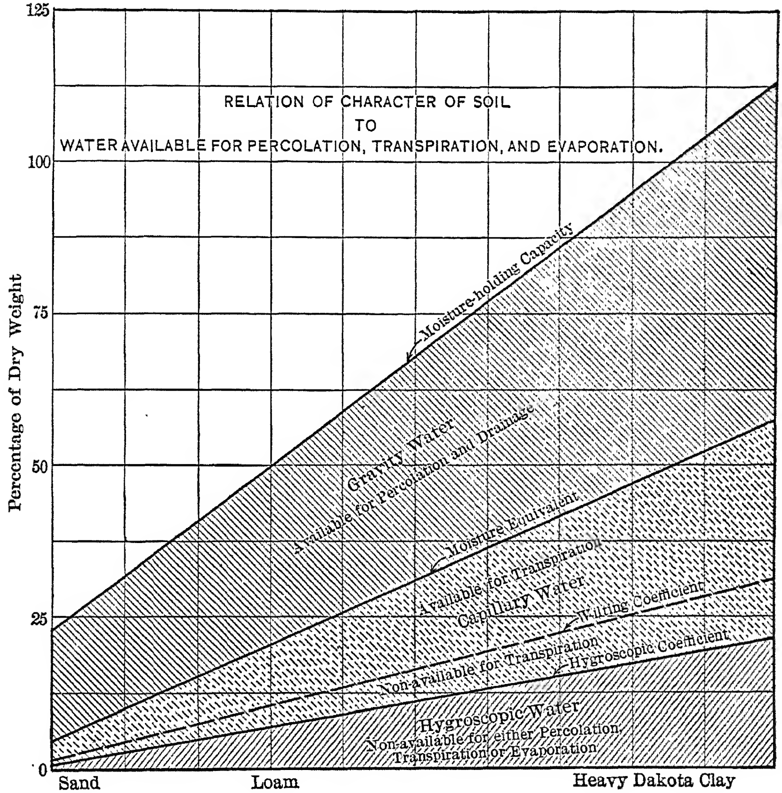


FIG. 169 (a).

about 2 per cent of its weight. Silt can hold an amount equal to about 25 per cent of its weight and clay in highly powdered condition can hold an amount of water equal to 100 per cent of its dry weight.

The following table gives the standard classification of soil grains adopted by the U. S. Department of Agriculture.

* Briggs, Lyman J., and Shantz, H. L., Bul. 230, Bureau of Plant Industry, U. S. Department of Agriculture.

TABLE 30. — CLASSIFICATION OF SOIL GRAINS

Name	Diameter of grain, millimeters
Fine gravel	2 to 1 0
Coarse sand	1 to 0 5
Medium sand	0 5 to 0 25
Fine sand	0.25 to 0 10
Very fine sand	0.10 to 0 05
Silt	0 05 to 0 005
Clay	0 005 to 0

All particles held on a No. 200 sieve must evidently be classed as sand.

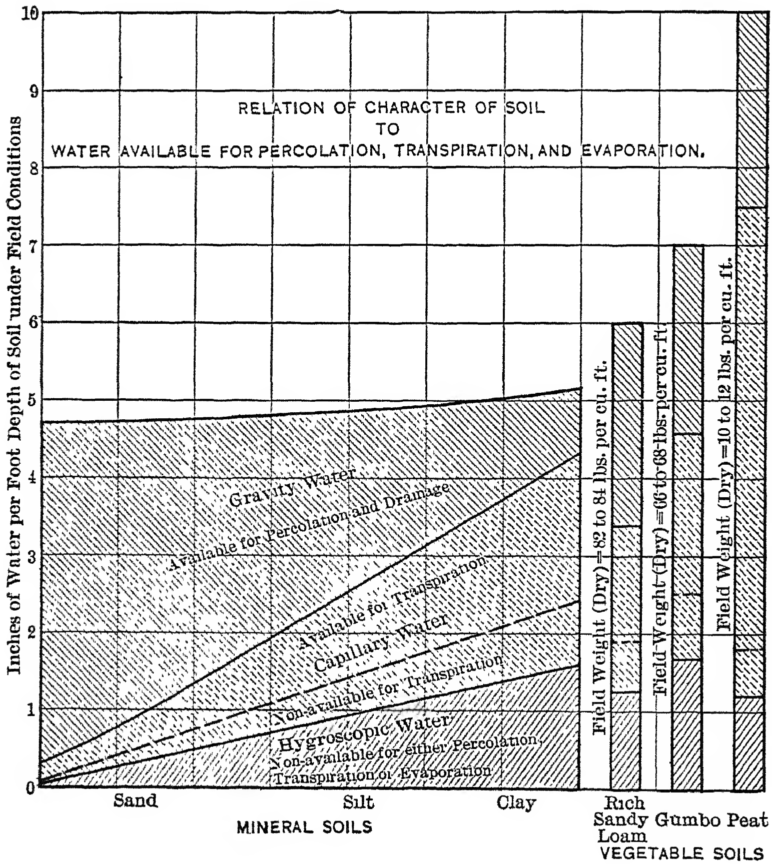


FIG. 169 (b).

Fig. 169 (b) is based primarily upon the author's studies of soils as they occur in the field. The moisture content is expressed in inches of water per foot depth of soil *under field conditions.*

The moisture available for plant growth in different soils under field conditions can be determined, approximately, by allowing .4 inch, per foot depth, for sand, 1.0 inch for silt, and 1.7 inches for clay, and taking a percentage of these quantities corresponding to the percentage of particles of the given size found in each foot depth of soil under field conditions.

The effect of vegetable matter is to greatly increase the capillary water and also, to some extent, the amount of gravity water which soils can hold.

Scientists in various fields have repeatedly stated that it is impracticable to express soil moisture in inches of water per foot depth of soil under field conditions. The author admits that from a laboratory viewpoint and under standardized laboratory methods, the determination of soil moisture in terms of the dry weight of the soil is the most exact measure available, but he contends that this measure affords no satisfactory indication of the relative moisture-holding capacities of various soils under field conditions. This contention is more forcibly presented by Fig. 169 (a and b) than by any arguments which can be made.

In determining the moisture-holding properties of different soils under field conditions the author has adopted the following method: A clod of undisturbed soil about the size of a man's fist is carefully dug up in the field and all loose particles are removed. Most moist soils will retain their shape very well, but where a tendency to crumble is manifested, thin, moist tissue-paper or a small piece of veil will offer the necessary support. The clod of soil is then immediately weighed and its volume determined by placing it in a container of known volume and filling all the remaining space with small shot. This virtually amounts to determining the specific gravity of the moist field soil by immersion in shot instead of water. Later, and at the observer's convenience, the dry weight of the material composing the clod of soil is deter-

mined by first vaporizing all of the moisture present and then weighing the material. These observations give the dry weight of a foot of soil under field conditions and also the moisture contained in a foot of soil in its given condition in the field. This field-moisture content, of course, may be more or less than that which the soil can hold by capillarity, depending upon the depth to the water-table and the climatic conditions which preceded the taking of the soil sample.

A representative sample of the dry soil is next selected and its specific gravity determined by immersion in water, by any standard method. From the specific gravity and the dry weight of a cubic foot of soil under field conditions the voids can be determined, and in this way the saturation water-content of the given soil under field conditions can be found.

The specific gravity of most mineral soils varies from 2.65 to 2.69. The presence of vegetable matter rapidly reduces the specific gravity.

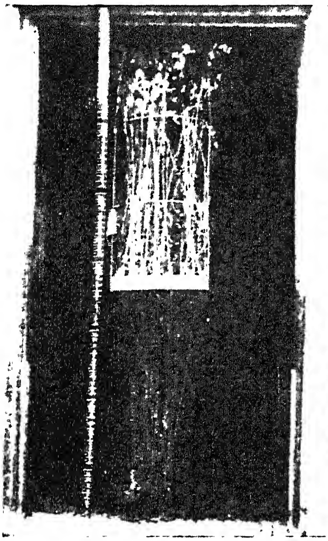
In testing for the amount of moisture which various soils can hold by capillarity the author first used soil columns 8 to 20 feet high and from 2 to 5 inches in diameter. It was found that the height of the soil column, when this was more than about 5 feet, had no influence on the moisture held by capillarity. It also appeared from tests of widely different soils placed in 1 foot layers on top of each other, in tubes, that the capillary water held by soils was a function of the character of the soil and not of the absolute amount of water held in the adjoining soil layers except in so far as a fine-grained soil lying on a coarse-grained soil would lose its gravity water very slowly. In view of these facts, tests for capillary moisture were next made by placing the soil sample on top of a permanent test column of very fine sand about six feet high. Clods of undisturbed soil, similar to those used in the volume determinations, were placed on top of the test column whose lower end was kept in water. The soil sample was then covered with very fine, wet sand, and then a little additional water was added. A water-sealed cover was then placed over the test column and after the excess water had drained down through the

sand column the soil sample was carefully removed, "pared" and the water-content determined.

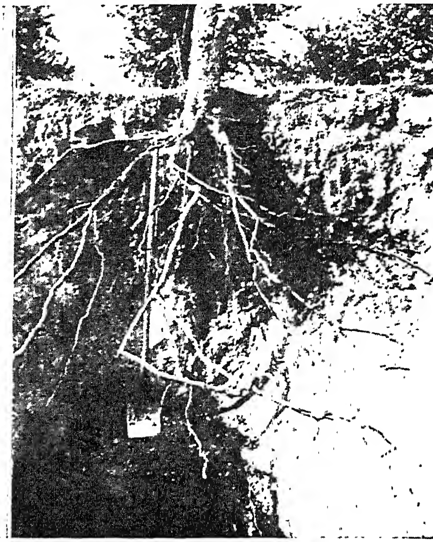
The rate at which the excess water is drained from the sample depends mainly upon its texture. In most cases the water loss which occurs between five and twenty days after placing the sample is small and inconsequential from a hydrological viewpoint. The finer the material constituting the test column, the greater the capillary pull and the sooner the excess gravity water is drawn down. Knowing the capillary water held by a given soil and its saturation water-content, the amount of gravity water which that soil can hold is also known, in practical terms, namely, *inches of water per foot depth of soil under field conditions.*

Effect of Character of Vegetation. — Even though all plants have been found to wilt when the moisture content for a given soil has been reduced to a certain percentage, the fact must not be lost sight of that in most fields the character of the soil varies greatly from foot to foot of depth, and that the roots of different forms of vegetation penetrate to widely different depths, usually adapting themselves, in a measure, to the available moisture content of the various soil layers. Frequent light sprinkling of lawns is well known to make the grass non-drought-resistant, because it coaxes the root system to the surface where the greatest supply of moisture is temporarily found. Typical root systems of plants are shown in Fig. 170.

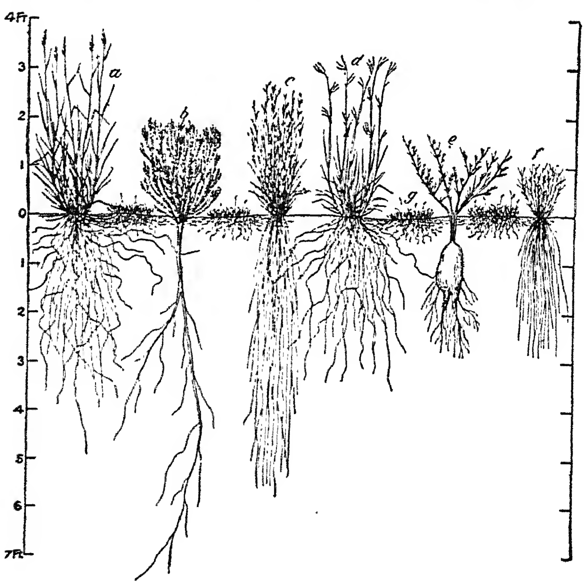
On the whole, the transpiration of deep-rooted vegetation will be less fluctuating with changes in monthly rainfall than that of shallow-rooted vegetation, on account of the deeper layer of soil from which the necessary moisture is drawn. In dry seasons deep-rooted vegetation will draw heavily on ground storage. The transpiration of shallow-rooted plants growing in sandy soils will vary more with rainfall than that of similar plants growing in clayey soils. When winter and spring precipitation is normally ample to more than supply the full requirement of capillary water for the entire depth of soil occupied by the root system, the transpiration of all plants growing



Oats



Peach Tree



Western Grasses

(a) Sand-grass; (b) sand-sage; (c) bunch-grass; (d) big bluestem; (e) bush morning-glory; (f) wire-grass; (g) black grama or short grass.

FIG. 170. — Typical Root Systems of Plants.

in sandy soils will vary more with the summer rainfall than that of similar plants growing in clayey soils.

Effect of Precipitation. — The character of vegetation is largely determined by precipitation and soil characteristics, hence, natural vegetation is a valuable index to both precipitation and character of soil.

On the loam soil of eastern Colorado, for example, a short-grass cover indicates 15 to 18 inches of annual precipitation. The root system of the grasses belonging to this association is well developed, but is limited to the upper foot of soil in which most of the moisture is found.

On the loam soil of west-central Kansas, with a rainfall of 22 to 24 inches per year, wire-grass is found. This grass grows taller than short-grass and extends its roots to a depth of about 3 feet, because the available moisture is found in the upper 3 feet of soil. Evidently, the increase of 6 to 7 inches in annual precipitation over western Kansas, as compared with eastern Colorado, has resulted in increased percolation.

On the loam soil of eastern Kansas, with a rainfall of 26 to 30 inches per year, bunch-grass, having roots extending about five feet down into the soil, is found. Still farther east, in the same latitude and under approximately the same conditions of temperature and rate of evaporation, where the rainfall is 35 inches or over and a well-defined water-table is found, forest growths predominate.

For similar conditions of temperature and 15 to 20 inches annual precipitation occurring largely during the summer months, a heavy soil will support only shallow-rooted vegetation, whereas a light soil will support deep-rooted plants.

It will be noted from Fig. 169 (b) that when a heavy soil has lost most of its available moisture, an inch of rain, even if it were all absorbed, would be held in the upper 6 or 8 inches of soil, whereas the same rainfall, if absorbed by a light soil, would penetrate the upper 2 feet of soil. As the heavy soil absorbs rainfall much more slowly than light soil, resulting in surface runoff, the depth to

which a given rain penetrates in a light soil will considerably exceed four times the depth of penetration in a heavy soil.

In connection with the distribution of natural vegetation as the result of differences in precipitation and character of soil, it is necessary to consider, also, the effects of evaporation. The higher the temperature and the lower the relative humidity, the greater the rate of evaporation and, consequently, the more rain required to grow any given plant on any given soil. For example, under practically uniform soil conditions, short-grass is found in northern Texas where the annual rainfall is about 21 inches, in eastern Colorado where it is about 17 inches, and in Montana where the annual rainfall is about 14 inches. The increased rainfall required in Texas to support short-grass on a given soil represents substantially the difference in the rate of evaporation between Texas and Montana.

The short-grass region is limited on the western slope of the Rocky Mountains by drought, and in central Texas, Nebraska, and Dakota by the deeper-rooted prairie grasses that kill out the short-grass by competition. Most of the eastern portion of the Great Plains was originally covered with prairie grasses which, in turn, gave way in the regions of higher precipitation, to forests. The region occupied, in a state of nature, by forests, almost invariably receives sufficient rainfall and has a soil that permits of sufficient percolation to form a well-defined water-table. Streams in such a region are, at least in considerable part, supplied by seepage flow. Regions occupied by natural upland grasses usually have no well-defined water-table except at depths far below the level of the streams. In such regions, the minor water courses are dry except after heavy rains and the larger streams not uncommonly lose water until, in some cases, they disappear entirely. Their ability to maintain an existence depends, primarily, upon the degree of imperviousness of their beds and banks.

Transpiration Proportional to Dry Matter Produced. — Most experimenters have found that the quantity of water transpired

by plants varies, approximately, as the quantity of dry substance produced. Whether or not this relationship is purely accidental does not invalidate the fact. In the 1903 Yearbook of the U. S. Department of Agriculture, is given the average yield of corn, for 15 years, in the principal corn-growing states, together with the average precipitation over those states during June, July, and August. When platted, these data indicate an average yield of 5 bushels, plus 2 bushels for every inch of rainfall during June, July, and August, between the limits of yields of 15 and 35 bushels per acre.

The data on water requirements of crops, recorded in Bulletin 177, Office of Experiment Stations, and Bulletins 130, 188, and 201, Bureau of Plant Industry, U. S. Department of Agriculture, though not conclusive, indicate that the yield of grain is approximately proportional to the quantity of water consumed. Soil evaporation and transpiration are not fully differentiated, however, in most of these experiments.

Livingston * gives considerable experimental data which show an almost direct relationship between transpiration and weight of vegetable substance produced.

The ratio of water used to dry substance produced has been found to vary with individual plants and with the plant environment. Conifers, in particular, have been found to use less than deciduous trees; in fact, some experimenters hold that they use less than one sixth as much. For grass and grain, the ratio of pounds of water used, to pounds of dry substance produced, seems to vary from about 300 : 1 to 600 : 1.

A full review of the literature on the water requirements of plants is given by Lyman J. Briggs and H. L. Shantz in Bulletin No. 285, Bureau of Plant Industry, U. S. Department of Agriculture. A summary of the most important observational data, taken from this Bulletin, on the water requirements of various plants, is given in Table 31.

* Livingston, B. E., Botanical Gazette, Vol. 40, p. 31.

TABLE 31. — SUMMARY OF WATER REQUIREMENTS OF VARIOUS PLANTS (Briggs and Shantz)

Crop	Lawes, 1850, Rothamsted, England	Wollny, 1886, Munich, Germany	Hellriegel, 1883, Dahme, Germany	King, 1892 to 1895, Madison, Wis.	Von Seelhorst, 1896 to 1898, Gottingen, Germany	Widtsoe, 1909, Logan, Utah	Leather, 1910–11, Pusa, India	Briggs and Shantz, 1913, Akron, Colo.
Wheat	235	...	359	...	333	546	554	507
Oats	...	665	401	541	...	...	469	614
Barley	258	774	297	388	365	...	468	539
Rye	...	...	377	...	386	...	...	724
Corn	...	233	...	350	...	386	337	369
Sorghum	...	...	...	...	...	...	437	306
Millet	...	447	...	...	...	...	...	275
Beans	214	...	...	...	...	...	...	...
Peas	235	416	292	477	...	843	563	800
Clover (red)	251	...	330	481	...	...	...	...
Clover (sweet)	...	...	...	...	...	...	...	709
Alfalfa	...	...	...	...	...	...	...	1068
Horse beans	...	...	263	...	...	...	...	...
Lupine	...	...	373	...	...	...	...	...
Chick-peas	...	...	...	...	...	...	818	...
Buckwheat	...	646	371	...	...	...	...	578
Rape	...	912	337	...	...	...	...	441
Mustard	...	843	...	...	...	...	496	...
Sunflower	...	490	...	...	...	...	...	...
Potatoes	...	...	...	423	281	...	...	448
Linseed	...	...	...	...	...	...	807	...
Eleusine	...	...	...	...	...	...	263	...
Paspalum	...	...	...	...	...	...	312	...
Cajanna	...	...	...	...	...	...	635	...
Cyamopsis	...	...	...	...	...	...	598	...
Rice	...	...	...	...	...	...	811	...
Sugar cane	...	...	...	...	...	...	212	...
Sugar beets	...	...	...	...	...	497	...	377
Salsola	...	...	...	...	...	...	...	336
Amaranthus	...	...	...	...	...	...	...	303
Artemisia	...	...	...	...	...	...	...	765

In view of the substantially constant relationship, as found by most experimenters, between transpiration and vegetable substance produced by any given species of plant, yields of hay, grain, etc., become a convenient index to the approximate, relative quantities of transpiration to be expected on different watersheds, and on the same watershed in different years.

Amount of Transpiration in Inches Depth over Ground Area. — No more uncertain factor enters into computation of rainfall losses than the amount of water used by growing plants. Most of the available data are inapplicable to the problem or so

widely divergent as to be of little value. Laboratory results are usually based on experiments with single plants, with no indication of the ground space covered by the plants. The time over which the observations extended and relevant meteorological data are usually missing. Frequently, transpiration is compared with other phenomena, such as evaporation from water or soil surfaces, or precipitation. The divergence of opinion with respect to the amount of transpiration is well indicated by the fact that Schleiden thought the transpiration from a forest was three times the evaporation from a water surface of equal area, whereas Shübler thought it only one quarter as great. Extreme values given for annual transpiration vary from less than 1 inch to 16 feet! Most of the values given for forest trees and small grains, however, vary from 4 to 9 inches per year, with occasional values for oats and some grasses running up to 14 and 15 inches per year.* If plants, under field conditions, transpired a quantity of water equal to from one half to two times the evaporation from an equivalent surface of water, as claimed by some experimenters, a great many streams in the United States that have a very appreciable, sustained flow would become intermittent, because there would be no ground-water supply to feed them. Surface runoff alone would appear in these streams.

* The experimental determinations of the transpiration of various plants, as given by Risler, Höhnel, Shübler, Hales, Hartig, Hellriegel, Sachs, Wollny, and others, are so divergent that the author felt it was of questionable utility to present these results here, except as briefly summarized above.

In most instances, only abstracts of the published results of these investigators were available to the author. These abstracts were so lacking in essential, related, meteorological phenomena as to make the transpiration determinations of relatively little value for present purposes. Frequently, daily transpiration would be stated, without reference to length of growing season, hours of sunshine, temperature, humidity, etc.

In published abstracts of the investigations above referred to, deductions, as to water consumption of plants, have frequently been made, based on some assumed length of season, and the like. Where experimental data were given for single trees, for example, a certain number of trees were assumed per acre, for the purpose of deducing a value of transpiration in inches depth on the ground area.

In the Monthly Weather Review for November, 1923, Horton made available in English, for the first time, the excellent observations on transpiration by Franz von Höhnel, originally published in German in 1879.

In estimating the transpiration loss from a watershed, the exact character of the vegetation is not as important a factor as it might at first appear. Except for unoccupied lands in the arid and semi-arid region, hardly a watershed of considerable size can be found that is given over purely to one class of vegetation. Practically all watersheds are covered with mixed vegetation, including trees, shrubs, grasses, or grains. Cut-over watersheds quickly grow up to grasses, weeds, and herbs

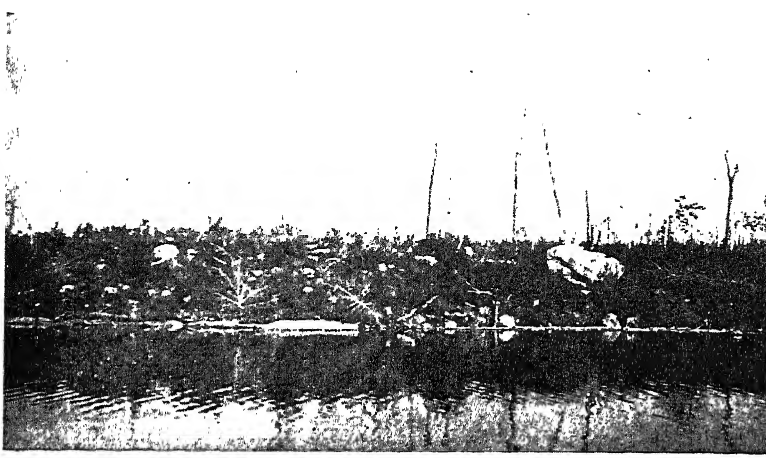


Fig. 171. — Rocky, Burnt-over Watershed thoroughly covered with Vegetation.

of various kinds, which in turn are soon supplanted by shrubbery, brush, and then a growth of young trees. Areas of agricultural land not under cultivation, or after harvest and before fall plowing, soon become thoroughly covered with self-sown grain, weeds, and grasses, and hence suffer a transpiration loss perhaps fully as high as though they were producing crops. Even the rugged watersheds of mountain ranges, below the timber line, are usually well covered with brush, grasses, moss, and other forms of low-growing vegetation. Burnt-over watersheds with scanty covering of soil, and rock outcropping everywhere, as in the northeastern part of Minnesota, are also well

covered with vegetation of one kind or another, as is shown in Fig. 171. As a consequence, the normal transpiration loss, so far as it is determined by the character of vegetation on different watersheds, does not vary between wide limits.

For tentative purposes, the following normal seasonal transpiration may be used as a base value in estimating water losses for the north central portion of the United States:

9 to 10 inches for grains, grasses and agricultural crops;
8 to 12 inches for deciduous trees;
6 to 8 inches for small trees and brush;
4 to 6 inches for coniferous trees.

These quantities represent inches depth of water over the entire area occupied by the given form of vegetation. The monthly distribution of this total seasonal transpiration is determined mainly by the monthly mean air temperature as given in Fig. 164, page 263. These base values of monthly transpiration must then be modified for deficient or excess precipitation and ground-water supply in the soil occupied by the root system of the given form of vegetation, to ascertain the probable monthly transpiration under the given conditions.

As here considered transpiration does not include interception, which is treated as one phase of evaporation from the land area.

CHAPTER VIII

DEEP SEEPAGE

The Underground Reservoir. — The presence of artesian water supplies over large areas in the United States is conclusive proof that some precipitation seeps down through the upper layers of soil and subsoil into the underlying rock strata. The percolating water flows along through these porous strata until they have dipped down below impervious strata and entrapped the water in underground reservoirs, from which it may again be drawn by deep wells, or from which it may eventually flow to the sea.

The term deep seepage, as here used, does not include the percolating precipitation which moves through the drift covering the rock strata and furnishes the seepage flow of streams. The actual amount of deep seepage can never be accurately determined, yet when we consider the fact that the entire domestic water consumption is equivalent to only about .1 inch of rainfall per annum and that only a relatively few artesian sources of supply are in use and that such supplies have frequently been found to become reduced and even exhausted after a relatively few years' draft, it becomes apparent that the aggregate amount of deep seepage, in so far as abstractions or additions to the flow of streams is concerned, must usually be inconsequential.

It is not intended to convey the impression, however, that the total amount of underground water, extending down to the depth of about six miles, according to Van Hise,* at which the pressure of the overlying weight of rock becomes so great as to reduce the porosity to zero, does not aggregate a tremen-

* Van Hise, C. R., 16th Annual Report, U. S. G. S., Part 1, 1896, p. 593.

dously large quantity. Most of this great reservoir of underground water, however, calculated by Slichter * as amounting to about 565 *million*, million cubic yards, must always remain unavailable for direct use by mankind.

The available artesian water supply is determined by the area over which the pervious stratum, interspersed between two layers of impervious strata, outcrops, the amount of rainfall which percolates deeply into this outcropping stratum, and the rate at which the underground water can flow through the porous stratum toward the wells from which it is drawn.

While none of the rock strata, except when under tremendous pressure, can be considered as entirely impervious, granitic rocks usually contain less than 1 per cent of voids, limestone, from 1 to 5 per cent, while sandstones contain from 6 or 7 per cent, to more than 25 per cent of voids. Although the voids in clay are relatively large, the pore spaces are so small that most of the water is held by capillarity and that which can be drawn by gravity moves so slowly as to make clay strata relatively impervious.

Artesian waters are usually hard and often quite warm. Temperatures of 80 to 90 degrees are not uncommon in the Dakota basin.

Artesian Basins. — The principal artesian supplies in the United States are derived from the Potsdam and the St. Peter sandstone. The former lies between the impervious Archean rocks and the lower magnesian limestone, and the latter between the lower magnesian and the Trenton limestones. About 12,000 square miles of Potsdam outcrops and about 3000 square miles of St. Peter outcrops occur in central Wisconsin and eastern Minnesota. These sandstone strata have a slope toward the south and soon dip below the impervious limestone, creating the best artesian well region in the United States, in southern Wisconsin and Minnesota, throughout

* Slichter, C. S., The Motions of Underground Waters, U. S. G. S. Water Supply Paper No. 67.

Iowa, most of Illinois, northwestern Indiana and northern Missouri.

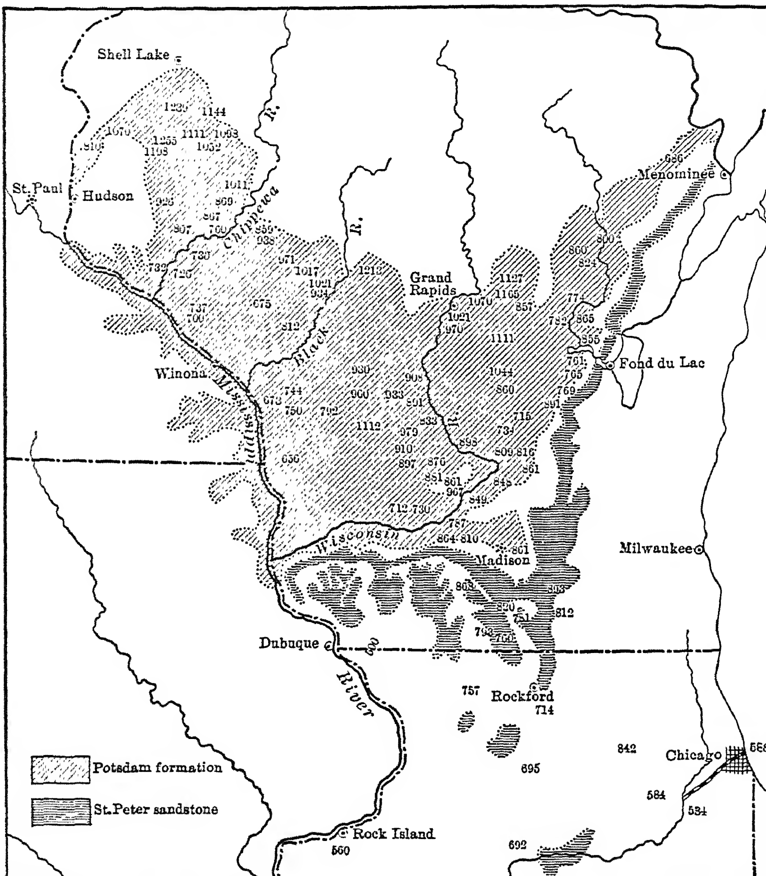
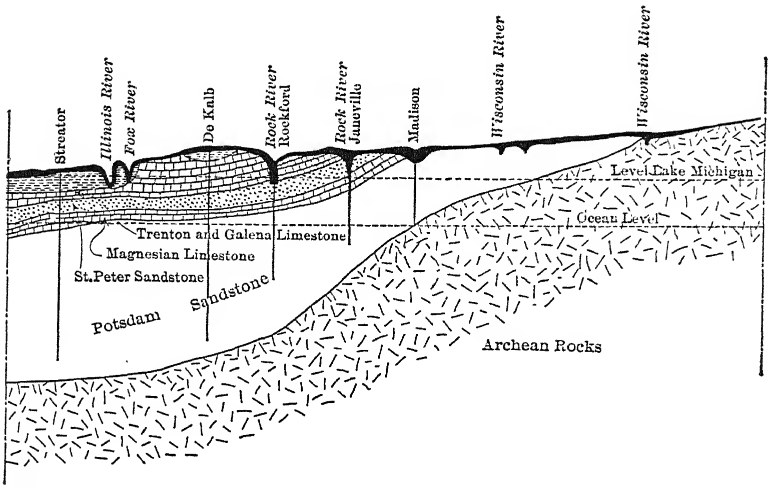


FIG. 172. — Outcrops of Potsdam and St. Peter Sandstones.
(Figures indicate elevation above sea-level.)

The Potsdam and St. Peter outcrops are shown in Fig. 172 and a section throughout this basin, based on a paper by Mead,* is shown in Fig. 173.

* Mead, D. W., The Hydro-geology of the Upper Mississippi River Basin, Jour. Assoc. Eng. Soc., 1894, p. 396.



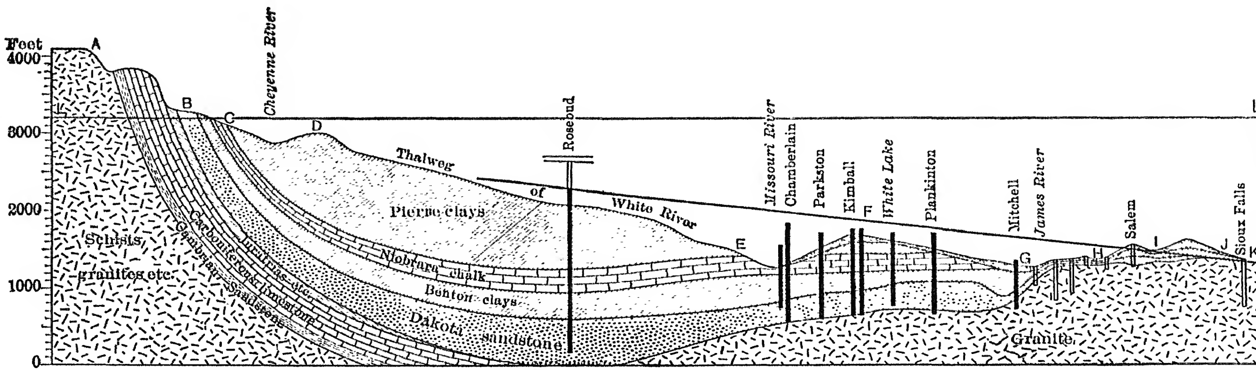
From a Paper by Daniel W. Mead, Jour. Assoc. Eng. Soc., 1894, p. 396.

FIG. 173. — General Arrangement of Water-bearing Sandstones.
(Section through southern Wisconsin and northern Illinois. Greatly enlarged vertical scale.)

As most of the outcropping sandstone is now covered deeply with glacial drift, usually containing thick layers of clay, the percolation of rain-water into these pervious sandstone layers is necessarily very slow. In fact, the existence of many small lakes and ponds seems to be possible only because the underlying clay is almost impervious. In most cases, percolation, however, is no doubt more than able to supply water more rapidly than the porous strata can conduct it away.

Numerous artesian wells in the upper Mississippi basin have been driven to considerable depths, through the overlying drift, limestone and sandstone layers, and over 1000 feet into the Potsdam sandstone. This brings the bottom of the well far below the level of the sea.

Other large and important artesian well regions are those in Dakota, Texas, California and on the eastern slope of the Appalachian Mountains. Minor basins are found throughout the Rocky Mountain region. The Dakota wells are relatively deep and are noted for their high pressure. The water-bearing stratum is the Dakota sandstone of the cretaceous period,



From U.S.G.S. Water Supply Paper No. 67.

FIG. 174. — Section through Dakota Artesian Basin.

Wells shown are within a few miles of cross-section line, except the Rosebud Well which is 25 or 30 miles from the line and on much higher ground. The height to which water would rise in a closed tube at the various wells is shown by the heavy black lines. The vertical scale is necessarily greatly exaggerated.

outcropping on the eastern slope of the Rocky Mountains at an elevation of about 3000 feet above sea-level. A section through the Dakota artesian basin is shown in Fig. 174.

The Potsdam and the St. Peter sandstone strata, the former increasing rapidly in thickness toward the south, have a gentle slope toward the sea, and no doubt some of the deep seepage finds its way directly into the ocean through these strata.

Artesian supplies in the Gulf and South Atlantic Coast region are derived mainly from sand and gravel deposits underlying a hard blue clay. The waters are soft and very satisfactory for domestic purposes.

Great fresh water springs occur ten to fifteen miles out in the ocean from the Florida, Gulf shore at depths of 100 to 300 feet.

In 1886, wells in Pensacola, Fla., from 60 to 280 feet deep and one and one-half miles from shore, rose and fell 6 to 10 inches daily, "apparently with the tide."

Motion of Underground Water. — Ground water, flowing through the capillary interstices of the soil and the rock, moves very slowly. Even in relatively coarse sands, the rate of motion is only a mile or two a year. In gravel, the flow may reach several miles a year, depending largely upon the pressure head and the character of the material. Evidently, then, it would take water percolating into the Potsdam outcrop in Wisconsin, a great many years, possibly one or two thousand, to reach the Gulf of Mexico.

Some measured rates of underflow through superficial deposits are one-fifth to three-quarter mile per year in the Arkansas River basin, one-half to four miles per year in the Mohave River basin, one and one-fifth miles per year in the Republican River basin in Kansas, and about one-third mile per year on Long Island.

Poiseuille, in 1842, concluded, from experimental observations, that the flow of fluids through capillary interstices varied directly as the pressure. This was later verified for air by Meyer, and for water by Darcy, who in 1856 set forth the

relation between the velocity of flow, character of soil, pressure head and length of soil column in the following formula:

$$v = k\,\frac{h}{l},$$

in which

v = the velocity of the moving ground water;
h = the difference in pressure-head;
l = the length of the soil column;
k = a coefficient depending upon the character of the soil, especially upon the size of the soil grains. The size of soil grain was to be determined experimentally by Darcy's apparatus.

Hazen Formula. — In 1892 Hazen * produced the formula:

$$v = cd^2\,\frac{h}{l}\,(0.70 + 0.03\,t),$$

in which

v = the velocity of water in meters per day through the entire cross-sectional area;
t = temperature of water in °C.;
h = head acting on water;
l = length of soil column;
d = "effective size" of soil grains in millimeters;
c = a constant varying from 400 to 1000.

Hazen defined "effective size" as such a size that 10 per cent of the material is of smaller grains and 90 per cent of larger grains. Hazen found that the 10 per cent of small-size grains virtually determined the capacity of sands to transmit water.

In addition to using the term "effective size" in differentiating the sands tested by him, Hazen used the term "uniformity coefficient." This represents the ratio of the size of grain, which has 60 per cent of the sample finer than itself, to the effective size. Hazen indicated in his Report, that on the basis of the data from which his formula was derived, its application could

* Hazen, Allen, Report Mass. State Board of Health, 1892, p. 541.

only be justified for sands having a uniformity coefficient below 5 and an effective size of between .1 and 3 millimeters. He also remarked that sharp-grained material with uniformity coefficients below 2 would have nearly 45 per cent of open space, or porosity, as ordinarily packed, and sands having coefficients below 3, as they occur in the banks or artificially settled in water, would usually have 40 per cent porosity; with more mixed materials, the closeness of packing increases so that with a uniformity coefficient of 6 to 8, only about 30 per cent porosity would be obtained. In general, round-grained water-worn sands, according to Hazen, would give from 2 to 5 per cent less porosity than sharp-grained sands.

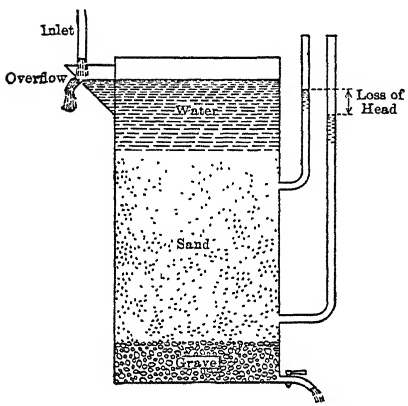


Fig. 175. — Hazen's Apparatus for Determining Flow of Water through Sand.

The apparatus used by Hazen in determining his law for the flow of water through sand is shown in Fig. 175 and the results obtained with the sand tested, which, according to Hazen's comment above noted, probably had a porosity of about 40 per cent, are given in Table 32. The values have been reduced from meters per day to feet per day.

The relative flow through the same sand for different water temperatures as determined by Hazen is given in Table 33.

Hazen found that for gravels of an effective size of about 3 millimeters, the general formula was not exactly applicable, as the velocity no longer increases as rapidly as the square of the effective size. Coarse gravels, also, indicate a velocity varying as the square root of the head, instead of the first power of the head, as in the case of sands. The effect of temperature also becomes less marked in the case of gravels.

TABLE 32. — FLOW OF WATER THROUGH SAND (Hazen)

Temperature = 50° F.
Uniformity coefficient less than 5 (apparently about 2.5)
Porosity, about 40%
Gradient $\frac{h}{l} = 1$

	Effective size in millimeters						
	0 10	0 20	0 30	0 40	0.50	1.00	3 00
Discharge *	33	131	295	525	820	3280	29,500
Velocity †	82	328	738	1312	2050	8200	73,800

* Discharge in cubic feet per day per square foot of gross cross-sectional area.
† Velocity (assuming 40 per cent porosity) in feet per day through actual pore space.

TABLE 33. — EFFECT OF TEMPERATURE ON FLOW OF WATER THROUGH SAND (Hazen)

Temperature, degrees F	32°	41°	50°	59°	68°	77°	86°
Relative velocity and discharge	0.70	0.85	1.00	1 15	1.30	1.45	1.60

Table 34 gives Hazen's results for coarse gravels of relatively uniform size, *i.e.*, having uniformity coefficients varying from 1.4 to 2.

TABLE 34. — FLOW OF WATER THROUGH GRAVEL (Hazen)

Temperature = 50° F.
Uniformity coefficient 1.4 to 2.0
Porosity = about 45%

$\frac{h}{l}$	Discharge in cubic feet per day through gross cross-sectional area for given effective size of grain in millimeters					
	3 mm.	5 mm.	10 mm.	20 mm.	30 mm.	40 mm.
0 0005	11.5	32.8	98.4	262	492	820
0.0010	23.0	68.9	190.0	485	902	1476
0 002	46.0	131.0	361.0	902	1575	2330
0 004	88.5	252.0	682.0	1575	2430	3280
0.006	134.5	367.0	902.0	2035	3050	4060
0.008	177 0	465 0	1115.0	2360	3580	4750
0.010	220.0	567.0	1262.0	2720	4000	....
0.015	322.0	780.0	1575.0	3380	4850	....
0 020	416.0	984.0	1902.0	3870	....	....
0.030	606 0	1310.0	2460.0	4750	....	....
0 050	918 0	1836.0	3480.0	....	....	....
0 10	1625 0	3050.0	5080.0	....	....	....

Slichter's Formula. — Slichter,* on the basis of a theoretical investigation, verified, however, by a long series of carefully conducted experiments by King,† determined the following equation for the flow of water through sand:

$$q = 0.2012 \frac{hd^2s}{ulK} \text{ cubic feet per minute,}$$

where

h = head acting on water;
s = cross-sectional area of soil column;
l = length of soil column;
d = mean size of soil grains in millimeters;
u = a coefficient depending upon the temperature;
K = a coefficient depending upon the porosity of the soil.

Slichter defined "mean" or "effective size" as such a size "that if all the grains were of that diameter, the soil would have the same transmission capacity that it actually has."

When the cross-sectional area term is omitted, Slichter's formula also reduces to the original Darcy formula, namely:

$$v = k \frac{h}{l} \text{ with } k \text{, however, a variable.}$$

Poiseuille, Meyer, Darcy, Hazen, and Slichter all agreed that the flow of water through capillary interstices varies directly as the pressure-head and inversely as the length of the soil column. King ‡ found a slight tendency for flow to increase somewhat faster than pressure.

Darcy's formula took account only of pressure-head and length of soil column. Hazen added the effect of temperature and size of soil grain, stating an approximate value for porosity. Slichter's formula includes not only pressure-head, length of soil column, effective size of soil grain, and temperature of water, but a great range of porosity.

* Slichter, C. S., 19th Annual Report U. S. G. S., Part II, 1899, p. 295. The Motion of Underground Water, U. S. Water Supply Paper No. 67.
† King, F. H., 19th Annual Report U. S. G. S., Part II, 1899.
‡ King, F. H., 19th Annual Report U. S. G. S., Part II, 1899, p. 59.

Table 35 gives the effect of temperature on the flow of water through sand columns as given by Slichter.

TABLE 35. — EFFECT OF TEMPERATURE ON FLOW OF WATER THROUGH SAND (Slichter)

Temperature, degrees F.	32°	40°	50°	60°	70°	80°	90°	100°
Relative velocity and discharge	0 74	0 85	1 00	1 16	1.34	1 51	1 70	1.90

Table 36 gives the transmission constant k or the discharge in cubic feet per day, through a soil column 1 foot long, under a head of 1 foot of water.

TABLE 36. — FLOW OF WATER THROUGH SAND (Slichter)

Temperature = 50°

Porosity = 40%

Gradient $\frac{h}{l} = 1$

	Silt		Very fine sand			Fine sand		
Diameter (mm.)	0 01	0 02	0 04	0 06	0 08	0 10	0 15	0.20
Discharge *	0.11	0 43	1 74	3.92	6 95	10.9	24 4	43 5
Velocity †	0 28	1 07	4 35	9 80	17 35	27 3	61.5	109 1

	Medium sand		Coarse sand			Fine gravel			
Diameter (mm.)	0.30	0.40	0.50	0 60	0.75	0.90	1 00	3.00	5.00
Discharge *	98 0	174.0	272.0	393 0	610.0	880.0	1088	9,770	27,100
Velocity †	244 0	435.0	680.0	983 0	1530.0	2200.0	2720	24,400	67,800

* Discharge in cubic feet per day per square foot of gross cross-sectional area.

† Velocity in feet per day through actual pore space.

The effect of porosity on the flow of water through sand as given by Slichter is shown in Table 37. The effect of porosity as given in this table represents the effect of packing the same sized grains in different ways.

TABLE 37. — EFFECT OF POROSITY ON FLOW OF WATER THROUGH SAND (Slichter)

Porosity, or per cent voids	26	28	30	32	34	36	38	40	42	44	46
Relative discharge	0 244	0 306	0 388	0 478	0.584	0 704	0 842	1.000	1 172	1 378	1 591
Relative velocity	0 376	0.437	0 517	0 597	0 687	0.781	0 886	1.000	1.118	1 251	1.385

Comparison of Formulas of Slichter and Hazen. — A comparison of the results of the investigations of Slichter and Hazen indicates that for a given slope and for all effective sizes from .1 mm. to 3 mm., Hazen found a discharge almost exactly three times as great as that found by Slichter.

Slichter defined "effective size" * as such a size "that if all grains were of that diameter, the soil would have the same transmission capacity that it actually has." Hazen defined "effective size" as such a size that 10 per cent of the material is of smaller grains and 90 per cent of larger grains. Although Hazen concluded that the particles which constitute the finer 10 per cent of the sample of sand virtually determine its transmission capacity, he nevertheless recognized the possible effect of the other 90 per cent of the particles, by stating that his formula was applicable only to sands having a uniformity coefficient less than 5. Apparently, Hazen's formula was based mainly on experiments with sands having a uniformity coefficient of about $2\frac{1}{2}$, possibly as low as 2.

Slichter's formula is based on a theoretical analysis, assuming uniform-sized, spherical grains. In so far as the formula was tested experimentally by King, uniform-sized grains were used. Slichter's results, then, assume a uniformity coefficient of 1. All natural sands have a uniformity coefficient greater than one. An increase in uniformity coefficients means a decrease in porosity, and, hence, a decrease in transmission capacity. The larger the grains for a given porosity, the greater the transmission capacity. The effective size of natural sands, then, of given transmission capacity must always be greater than the effective size of uniform-grained sand of the same transmission capacity. In other words, the effective size of Slichter's sand is always less than the effective size of Hazen's sand of equal transmission capacity. This, however, does not explain the almost exact difference of 300 per cent in the results as given by Slichter and Hazen for all effective sizes.

* The Motion of Underground Waters, pp. 22, 27.

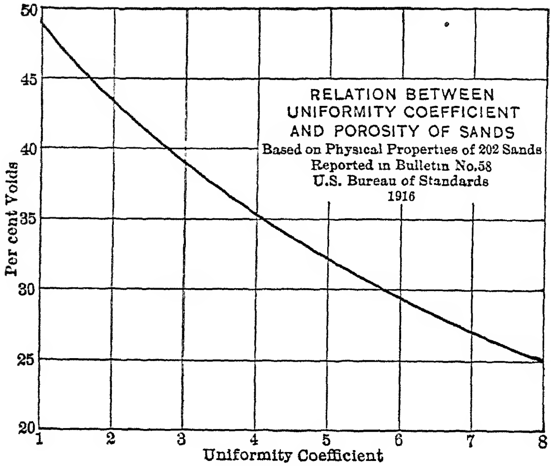


FIG. 176.

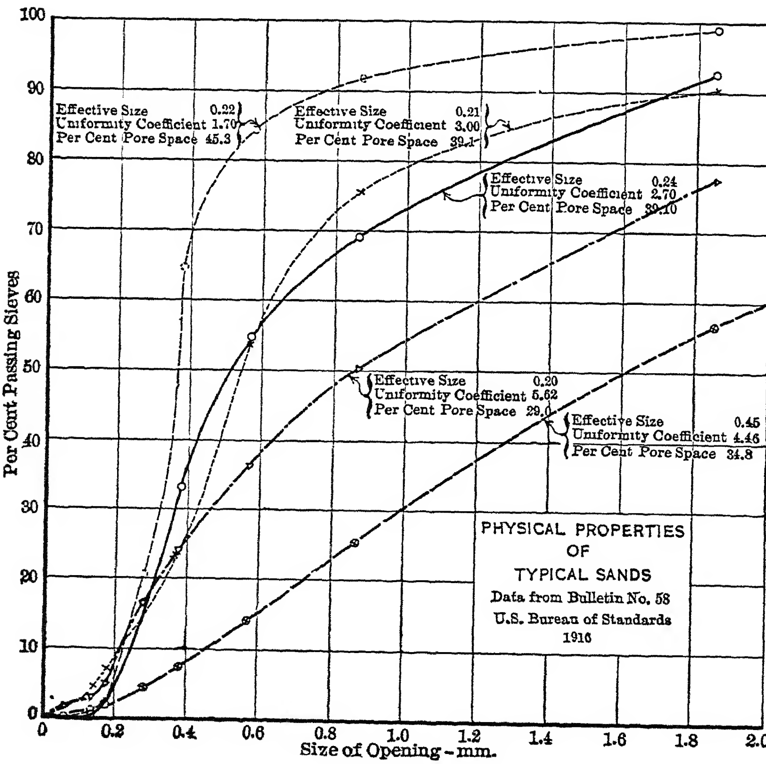


FIG. 177.

Fig. 176 based on the physical properties of 202 sands, reported in Bulletin No. 58, Bureau of Standards, U. S. Dept. of Commerce, June 20, 1916, shows the average relation between the uniformity coefficient and the porosity of sand. Although individual sands show considerable departure from the mean relationship here expressed, yet the data at hand show reasonable correspondence.

It will be noted that Hazen's general statement, page 289, regarding the effect of uniformity on porosity is in agreement with Fig. 176.

Fig. 177 shows graphically the physical properties of five widely different sands conforming to the above expressed relationship between uniformity coefficient and porosity.

Measurement of Underflow. — While the formulas previously discussed are of value in connection with works for the collection and filtration of public water supplies, and serve also to give a general comprehension of the movement of underground water, actual measurements of the velocity of underflow are frequently of great engineering value. The best form of apparatus yet devised for this purpose is that invented by Professor C. S. Slichter of the University of Wisconsin.

The essentials of the apparatus are shown in Fig. 178.

An electrolyte, usually ammonium chloride, or caustic soda, is introduced into a well and its movement registered by an ammeter placed in an electric circuit running between the casings of the wells. An electrode, placed in the lower well but insulated from its casing, is joined into the circuit. As the electrolyte flows with the ground-water toward the lower well, the current registered by the ammeter increases until, when the electrolyte reaches the lower well, a sudden rise in current due to a short circuit is registered. A typical graph of the results obtained in an actual measurement is shown in Fig. 179. The time interval between point A, which represents the instant when the electrolyte was introduced into the upper well, and point B (the point of inflection on the curve), which

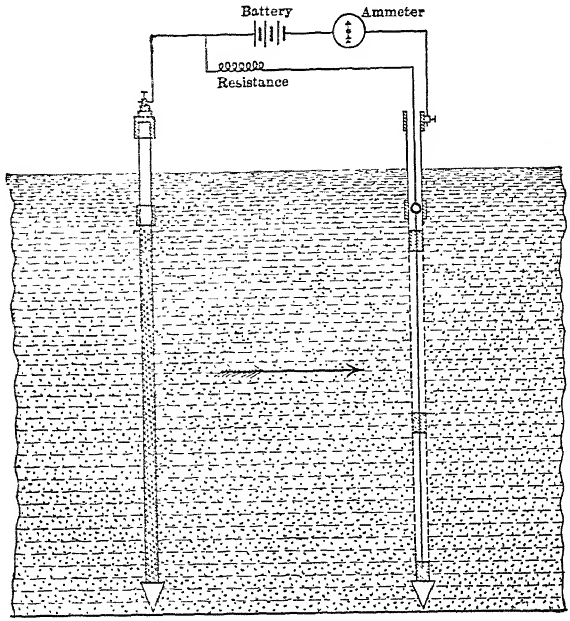


FIG. 178. — Slichter's Apparatus for Determining Flow of Underground Water.

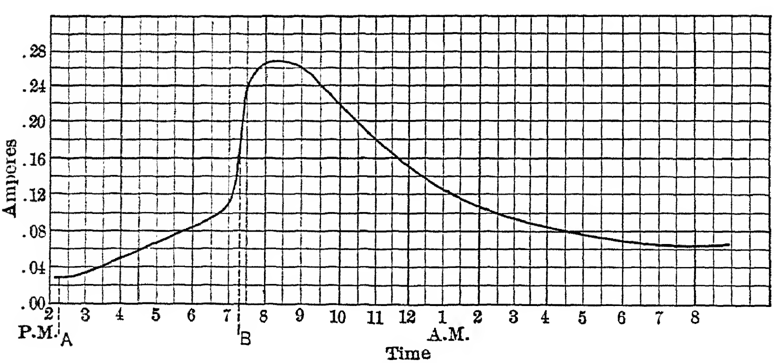


FIG. 179. — Curve obtained by Slichter's Method of Determining the Velocity of Ground-water.

(The distance AB represents the time of passage of the ground-water from the upper to the lower well. The point B should be taken at the point of inflection of the curve and not at the highest or maximum point. If the point of inflection be taken the effect of the diffusion of the electrolyte will be nullified. — Slichter.)

represents the time when it reached the lower well, is the time required for the ground-water to move between the two wells.

Knowing the velocity of flow, the pore spaces must be determined or estimated and from these two quantities the discharge per unit of cross-sectional area of porous stratum can be determined. The total amount of underflow, of course, depends also upon the total cross-sectional area of porous stratum under investigation.

CHAPTER IX

RUNOFF

Definition. — Runoff is the technical name applied to that portion of the precipitation which is carried off from the land area into the ocean through surface channels. It constitutes the residual precipitation after evaporation, transpiration, and deep seepage losses have been supplied. Being a *residual*, runoff necessarily cannot be a *percentage* of the rainfall, *i.e.*, the runoff must be determined by deducting losses from precipitation and not by taking a percentage of the precipitation.

Speaking in very general terms, the demands of evaporation and transpiration require from about 15 to 25 inches of precipitation per annum. The remainder represents runoff. Fig. 180 shows the approximate mean annual runoff in the United States, according to the U. S. Geological Survey.

SURFACE FLOW

Broadly speaking, runoff consists of surface flow and seepage flow. The factors modifying the surface flow will first be discussed. These factors may be subdivided into the character and rate of precipitation, and the physical characteristics of the watershed.

Effect of Precipitation and Temperature. — Large surface flow is ordinarily produced by heavy precipitation occurring in a short interval of time. In northern latitudes considerable precipitation may accumulate on the ground as snow, and a large portion of this may be suddenly carried into the streams by warm rains or high temperatures. In the Ohio Valley, for example, the precipitation is quite uniformly distributed through the year, amounting to about three to four inches per month.

Occasionally, a large portion of the winter precipitation falls as snow, remaining on the ground until it is carried off into the streams by warm spring rains or high temperatures or by a combination of the two.

Over the Northwest, the winter precipitation is relatively light, averaging only about 1 inch per month, but the temperatures are lower, so that considerable snow may accumulate during the winter months. The probabilities of high surface flow are less here than in the Ohio Valley, however, notwithstanding the winter's accumulation of snow, because the temperature rises rapidly in the spring, normally causing the melting of the accumulated snow before heavy rainfall sets in. Moreover, the ground, in the Northwest, usually freezes up while in a comparatively dry state and hence permits considerable percolation, in spring, even while still frozen.

In the Southwest, no snow accumulates, but the summer precipitation is much greater than in the Ohio Valley. High surface runoff here results from excessive precipitation over restricted areas.

Effect of Physical Characteristics of Watershed. — Given rates of precipitation cause different surface flows from watersheds of varying character and condition. An impervious, steeply sloping drainage area may shed substantially all of the rain falling upon it. A drainage area may be impervious on account of outcropping rocks, frozen and ice-covered ground, or saturation. Perhaps the highest degree of imperviousness is attained by saturated, frozen ice-covered ground. Substantially all of the rain falling upon such ground will run off into the water courses, occasionally carrying ice or snow with it in sufficient quantity to make the runoff exceed the rainfall. When sandy soil freezes up after thorough drainage has been permitted, it will remain more or less pervious and absorb a surprisingly large amount of rain after the ice cover has been removed, but before the frost is out of the ground.

A watershed, impervious on account of outcropping rocks,

nevertheless absorbs a moderate amount of water at the beginning of a rainstorm on account of the moss and humus found in the crevices of the rocks. After such storage capacity is exhausted, however, substantially all of the succeeding rainfall will run off into the water courses and into lakes, ponds, marshes and swamps, common to such watersheds.

When heavy rains continue for some time, all but the most sandy and gravelly watersheds become temporarily impervious through saturation of the soil. For any given rainfall, the total surface runoff from a pervious, sandy watershed will necessarily be less than that from other watersheds, by the amount of water required for saturation. Sandy watersheds frequently exhibit no signs of surface runoff. The presence of gullies is an unmistakable sign of surface runoff.

In the spring and fall of the year, when evaporation and transpiration losses are small, all soils, as a rule, carry substantially the entire possible amount of capillary water, between rains. Under such conditions, the capacity of sand for gravity water is about four inches per foot depth, whereas the capacity of heavy clay is but a little more than an inch. In consequence, clay soils quickly become saturated and permit large surface runoff. While clay soils nominally have great moisture holding capacity, not only is the rate of absorption of water very slow, but under field conditions clay soils hardly ever dry out except at the surface, so that their actual capacity for moisture is usually very much less than that of sandy soils.

Land under cultivation will, in the spring and fall, absorb considerable rain and thus reduce the surface runoff. All vegetation will retard the surface runoff somewhat, but its effect is soon lost in case of heavy rains. Virgin forest with deep humus cover, though of rare occurrence, has considerable absorptive capacity.

The steeper the slope of a watershed, the greater the surface runoff, but the effect of ruggedness is not as great as might be imagined. Leaving out of consideration very flat watersheds,

the effect of slope on the total surface runoff is relatively small. It affects, primarily, the *time* within which the surface waters reach the various channels.

Effect of Drainage of Upland. — Comparatively few observational data are available respecting the effect of tile and open ditch drainage on the flow of streams.* The views held by engineers regarding the effect of drainage are about as widely divergent as those regarding the effect of forests. Much of this divergence of opinion appears to be the result of reasoning from different premises.

The effect of drainage, as of forests, is not a single, uniform one. Believing that a statement of " effects " should always be coupled with a specific statement of the " conditions " under which these effects are produced, the author has endeavored, in the following pages, to deal with one phase of the subject of drainage and forests at a time. All but the very smallest watersheds are a combination of diverse characteristics; consequently the sum total of the effect of drainage and forests upon the flow of streams must be based upon an understanding, so far as our present knowledge permits, of how these factors influence stream flow under specific conditions.

Both open and tile drains placed in upland fields facilitate and hence increase surface runoff, but, on the whole, have an equalizing tendency. In so far as tile drains intercept water which has already passed beneath the surface of the ground, and bring it into open channels again, they must inevitably increase the total surface runoff and reduce the seepage flow. By maintaining a more open soil texture, and by quickly reducing the moisture content of the soil above them to that which the soil can hold by capillarity, *i.e.*, by removing gravity water amounting to from $1\frac{1}{2}$ to 4 inches per foot depth of soil, tile drains increase the capacity of the soil for absorbing water during rains, and thus tend to lengthen the time within which a given amount of runoff reaches the water course. In other words, tile drains on upland fields usually tend to equalize

* See "The Effect of Agricultural Drainage Upon Flood Run-off" by Sherman M. Woodward and Floyd A. Nagler in Proc. Am. Soc. C. E., Jan., 1928.

the surface runoff. During torrential summer rains, however, the rate of absorption of water by even the best drained heavy clay soils, is altogether too slow to prevent excessive surface runoff even from flat slopes. Open ditching, under such conditions, facilitates rapid surface runoff and increases flood flows.

Effect of Drainage of Swamps. — The drainage of swamps and bogs, particularly those having a heavy covering of peat vegetation and the water-table near the surface of the ground, usually has an equalizing effect upon the flow of streams. Peat vegetation, and the resulting humus following drainage and decay of the vegetable fiber, quickly absorbs large quantities of precipitation. As the pore spaces are large, however, such soil rather readily delivers up its burden of gravity water to the drains below. The temporary storage capacity of such vegetable soils, nevertheless, is greatly increased by drainage and the total evaporation loss is decreased. As, under the conditions assumed, the water-table was above the level of tile drains before the drainage system was established, drainage of such soils does not result in intercepting any large portion of the percolating water that supplies the seepage flow, hence this is not greatly reduced by drainage. Drainage of swamps and bogs with peaty soils, then, usually reduces the ordinary flood runoff, increases the total runoff, does not materially decrease seepage flow; in short, drainage of such soils tends to equalize stream flow.

Effect of Lakes and Ponds. — Ordinary surface runoff, resulting from moderate rains, is retarded and equalized and, to some extent, diminished, by lakes and ponds. All pond holes, no matter how small, have some retarding effect on runoff, tending to reduce the rate and extend the period of time over which runoff occurs. Ponds, in so far as they are wet-weather phenomena, may, to some extent, increase percolation. Lakes and other permanent bodies of water usually exist because percolation is nil or exceedingly slow. They are, as a rule, fed by both ground and surface waters, and, consequently, can-

not add to the ground-water supply through percolation. All permanent bodies of water greatly increase evaporation losses from a watershed by providing a continuous supply of moisture, and consequently reduce the total available runoff. The greater the depth of lakes, however, the lower their temperature and the smaller the evaporation loss.

Marshes and swamps whose beds are sufficiently impervious to maintain a supply of water throughout the year not only increase evaporation losses but greatly increase transpiration losses by sustaining a luxuriant growth of grasses or timber. Swamps and marshes, while tending to retard and equalize the ordinary surface runoff, greatly reduce the total quantity of water finding its way into the streams.

SEEPAGE FLOW

The water contributed to streams as seepage flow consists of ground-water supplied by percolation. Not all the percolating precipitation, however, appears in the streams. Some of it is lost through evaporation, some through transpiration, and on some wathersheds another, though usually small portion, is lost through deep seepage. When, through evaporation and transpiration losses, the capillary water, amounting to from half an inch in sand to three inches, per foot depth, in heavy clay, has become depleted, percolation must first replenish the capillary water before the soil will permit gravity to draw water down into the ground-water reservoir which supplies the seepage flow of streams.

Effect of Watershed Characteristics. — To be possessed of good seepage flow, a watershed must be of such a character that not only will the percolation of rainfall be large, but subsequent evaporation and transpiration losses small. When the precipitation is ample, the soil and underlying rock strata are usually the most important factors influencing seepage flow. Even on steep slopes, deep, sandy soil and subsoil will permit a large amount of percolation and will quickly carry

the percolating water to depths from which it is safe against return by capillary action. On such watersheds, all forms of vegetation, by reducing the moisture content of the surface soil, inevitably reduce the seepage flow.

Clay soils retard percolation, facilitate surface runoff and exert a large capillary lift in bringing moisture to the surface again for evaporation and transpiration.

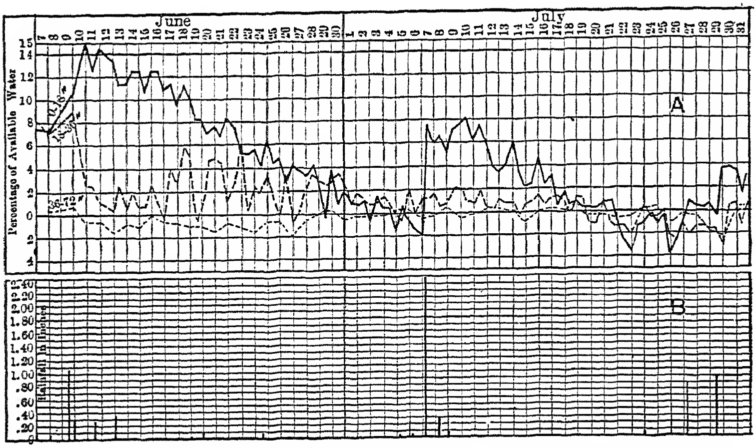


FIG. 181. — (*A*) Soil Moisture in Heavy Soil at Akron, Colorado, and (*B*) Precipitation, June and July, 1909.

The effect of even moderately heavy soil in preventing deep percolation is well shown in Fig. 181 from Bulletin No. 201, Bureau of Plant Industry and Department of Agriculture. The moisture indicated in the diagram is that available for plant growth in the given soil. It will be noted that during the entire period, the moisture content did not change below a depth of 3 feet and the heavy rain of 2.4 inches on July 7 did not penetrate below a depth of 18 inches. The increase in moisture content of the upper 18 inches of soil indicates that nearly half of the precipitation ran off into the streams. Under such conditions as these, there is no ground-water supply and hence the small streams, at least, are necessarily intermittent. The season's records for this region indicate that practically

no surface runoff results from a rainfall of less than $\frac{1}{2}$ inch. When from $\frac{1}{2}$ to 1 inch of rain falls in a short time, about a tenth of an inch runs off, and when over 1 inch falls in the course of a day from two to five tenths of an inch runs off.

Swamps and marshes decrease both surface and seepage flow. Wet-weather ponds, particularly on rolling, sandy watersheds, increase seepage flow as they are merely depressions that become filled during rains and soon disappear, largely through percolation. On clayey watersheds wet-weather ponds may disappear mainly through evaporation. Swamps and marshes on very flat, clayey watersheds usually yield little runoff when the annual rainfall does not considerably exceed 20 inches.

By intercepting percolating water that has already reached a point several feet below the surface of the ground in its path toward the ground-water reservoir, tile drainage reduces seepage flow.

Where impervious rock strata, sloping with the valley, underlie glacial drift, and where such rock strata outcrop in the river bed, there is usually a large increase in seepage flow for some distance upstream from the point of outcrop.

Effect of Character of Precipitation. — When the precipitation is insufficient to keep the ground continually moist, which is usually the case, the character and rate of precipitation are the factors which most largely influence seepage flow. When there is no frost in the ground, or the ground was relatively dry when it froze, slowly melting snow permits of the greatest percolation. On the whole, a greater proportion of snowfall than of rainfall eventually percolates into the ground to supply seepage flow.

Next to snowfall in effectiveness in replenishing the groundwater supply are the slow drizzling rains that occur over large portions of the country during spring and fall when both transpiration and evaporation demands are relatively small. It is not unusual for the entire summer precipitation to be held in the upper layers of soil as capillary water, or to run off

into the streams over the surface of the ground, none of it percolating to supply seepage flow.

Changes in Seepage Flow Following Percolation. — Just before the spring break-up in the Northwest, the seepage flow which, together with the outflow from lakes, constitutes the entire flow of streams during the winter months when the precipitation is all stored on the surface of the ground as snow, has reached its minimum and has also become quite uniform. The increase in seepage flow which will result from a given increase in ground-water supply, through percolation, will depend upon the slope of the ground-water surface and the resistance of the subsoil to the flow of water. As previously stated, the flow of ground-water is directly proportional to the head and to the square of the effective size of the grains of the conducting material. Fine-grained subsoil,* by offering great resistance to flow, will maintain the ground-water table at a very much steeper slope than coarse-grained material. Character of subsoil, then, is a far more important factor in determining the shape of the water-table than ground surface topography.

As the ground-water rises, by capillarity, several feet above the level of saturation as is well shown in Fig. 182, and as the plane of saturation is usually so far below the ground surface as to protect the ground-water from evaporation, and from transpiration of all plants except possibly forest trees, equal amounts of percolation must raise the level of saturation by uniform amounts in any given soil. Fig. 182 shows that a given amount of percolation will raise the plane of saturation 80 per cent more in clayey soil than in fine sand and 10 to 15 per cent more in fine sand than in coarse. As the head causing flow in the fine sand is about ten times as great as that causing flow in the coarse sand, the increased head due to a given

* For the purposes of hydrology, the author uses the term "soil" to mean the upper layers of earth from which most plants primarily derive their sustenance, *i.e.*, the upper three or four feet. The term "subsoil" is applied to all the intermediate layers of earth between the soil and the underlying rock strata.

amount of percolation has proportionately much less effect in increasing seepage flow in the case of the fine sand or clay. A given amount of percolation, then, will result in a much greater increase in seepage flow in the case of the watershed underlain

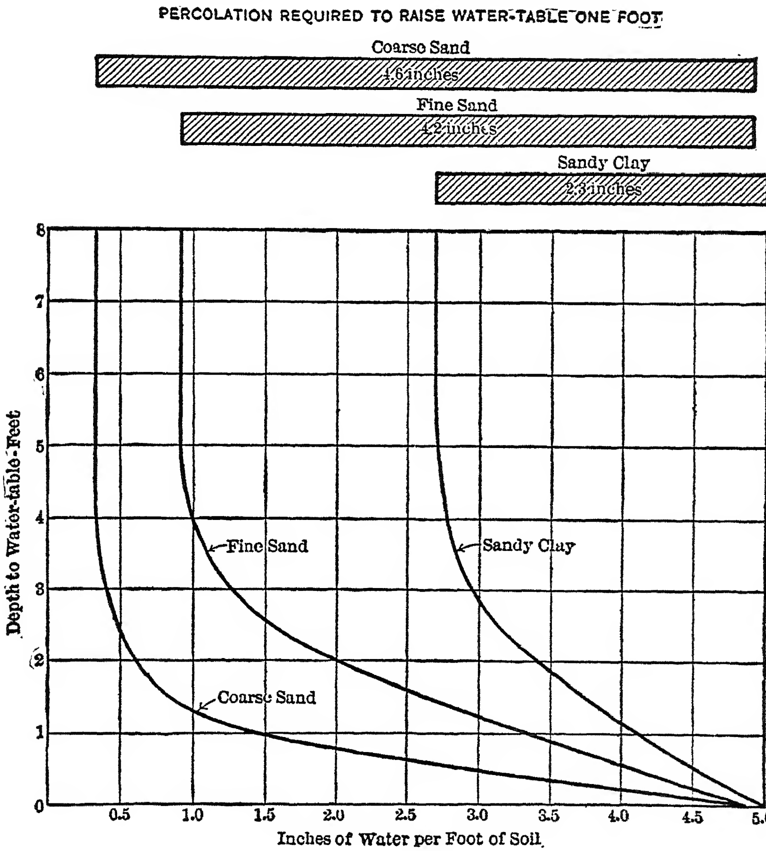


Fig. 182. — Rise of Ground-water by Capillarity, and Percolation required to raise Water-table One Foot in Different Soils.

with coarse material. It follows from this, that a watershed in which the plane of saturation usually lies in coarse, porous material will experience the greater variation in seepage flow.

Depth of Water-table. — On some watersheds the water-table lies so close to the surface of the ground that some of the ground-water is held back during the frozen season, resulting in minimum stream flow during the sub-zero weather of mid-winter. On other watersheds, there is no well-defined water-table except at elevations below the water courses. Streams draining such watersheds, particularly if lying in regions where the ground remains frozen during several months, often reach a stage of zero flow.

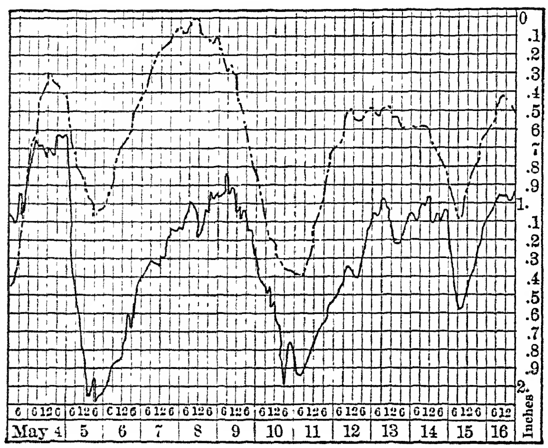


FIG. 183. — Effect of Barometric Pressure on Flow of Spring (after King).

Effect of Barometric Pressure. — King * found that the flow of water from springs, tile drains and artesian wells reflected changes in barometric pressure. This fact is well shown in Fig. 183. Although the diagram is not fully dimensioned, yet the synchronism of the phenomena is clearly shown. Reduced pressure results in increased flow from springs and wells.

A phenomenon intimately related to the flow of water from springs is the "breathing" of wells. One of the best of the available records of this kind is that published in the Monthly Weather Review of February, 1916. The essential data are

* King, F. H., 19th Annual Report, U. S. G. S., p. 73.

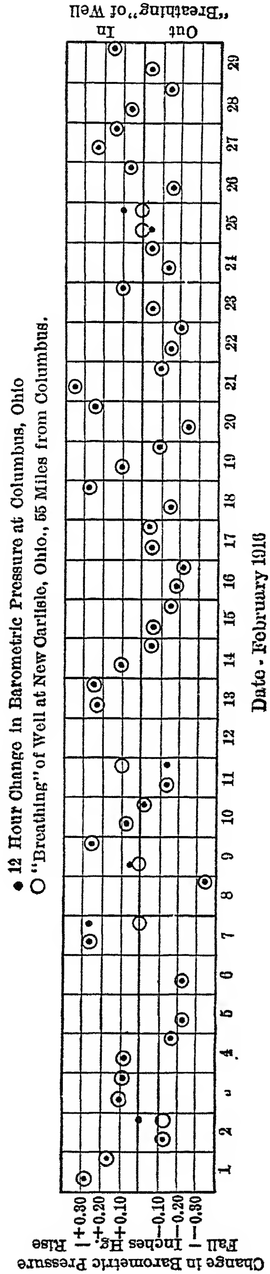


FIG. 184. — Effect of Barometric Pressure on "Breathing" of Well.

presented graphically in Fig. 184. With very few exceptions the air moved into the well when the barometric pressure was rising and out when it was falling.

RUNOFF FROM TYPICAL WATERSHEDS

Climatological, topographical and, to some extent, also, cultural conditions on a watershed, are reflected in the flow of its streams. Figs. 185 to 194 show the monthly mean tempera-

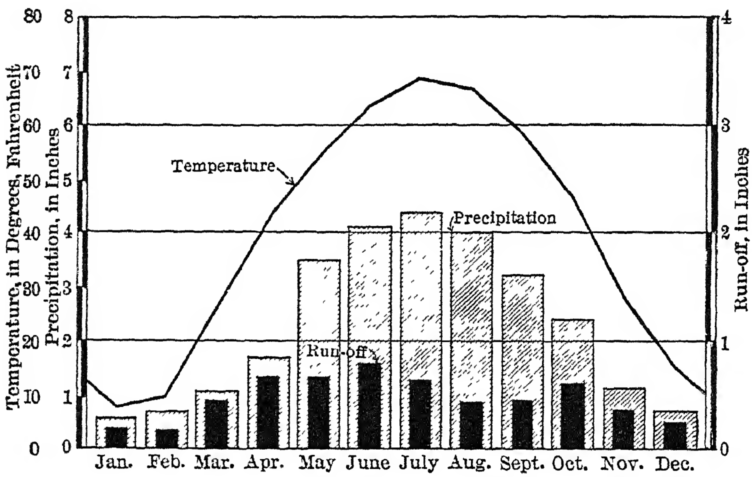


FIG. 185. — Temperature, Precipitation and Runoff, Mississippi River Watershed, Minneapolis, Minn., 1897–1913. Area, 19,500 sq. mi.

ture, precipitation and runoff for typical watersheds in widely different sections of the United States, for the purpose of illustrating the effect of temperature and precipitation on the total amount of runoff.

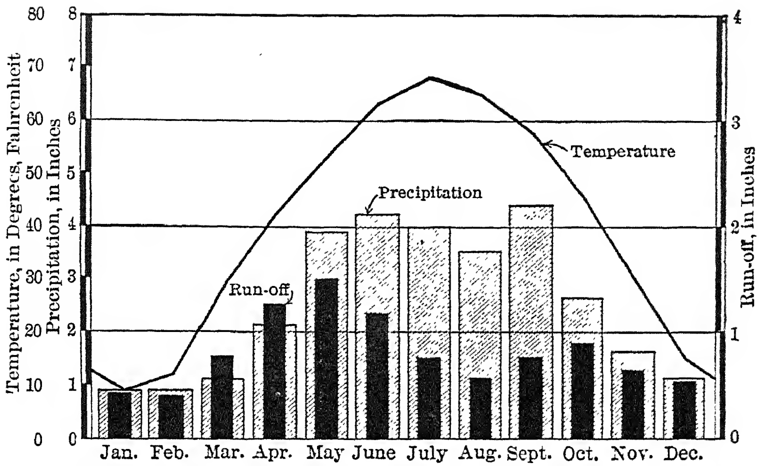


FIG. 186. — Temperature, Precipitation and Runoff, St. Croix River Watershed, St. Croix Falls, Wis., 1901–1912. Area, 5930 sq. mi.

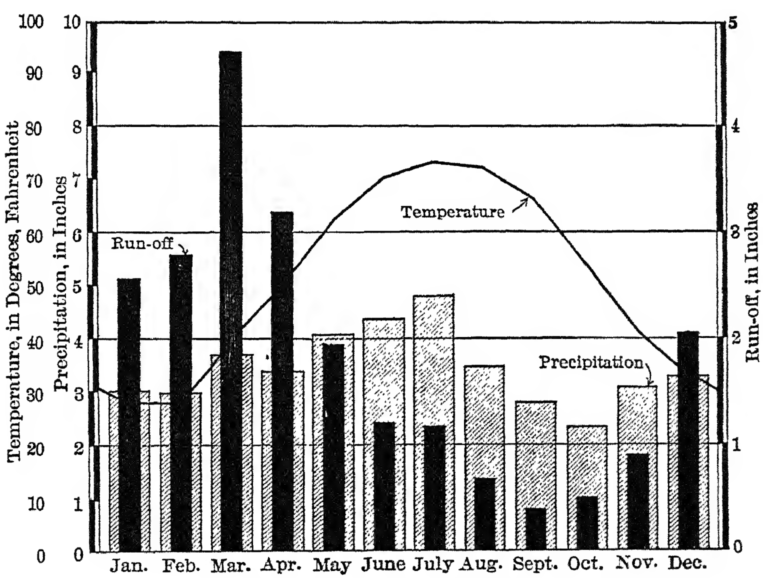


FIG. 187. — Temperature, Precipitation and Runoff, Ohio River Watershed, Wheeling, W. Va., 1891–1905. Area, 23,820 sq. mi.

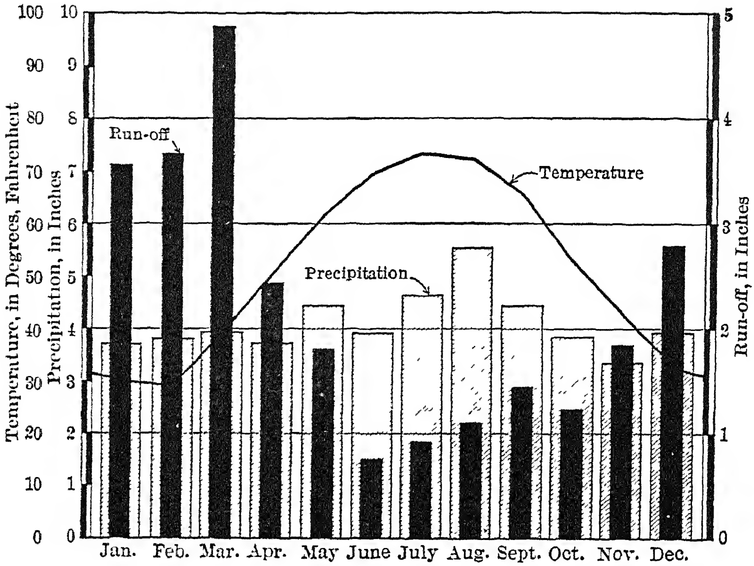


FIG. 188. — Temperature, Precipitation and Runoff, Tohickon Creek Watershed, Point Pleasant, Pa., 1887–1911. Area, 102 sq. mi.

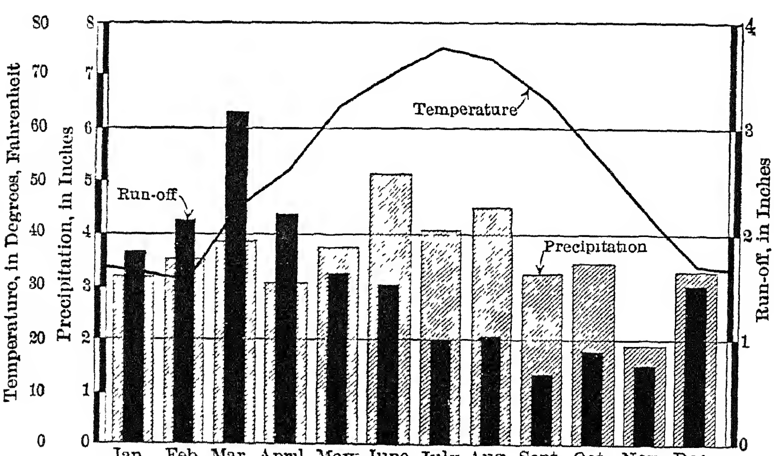


FIG. 189. — Temperature, Prescription and Runoff, James River Watershed, Cartersville, Va., 1898–1905. Area, 6230 sq. mi.

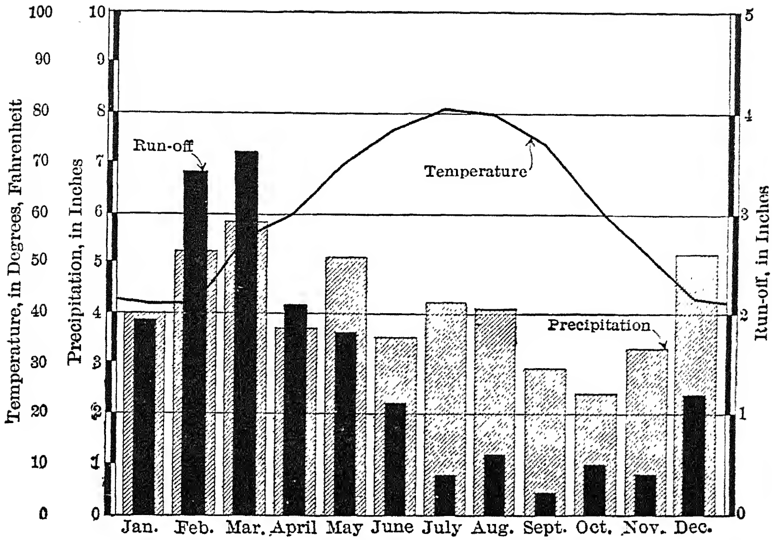


FIG. 190. — Temperature, Precipitation and Runoff, Tombigbee River Watershed, Columbus, Miss., 1900–1909. Area, 4440 sq. mi.

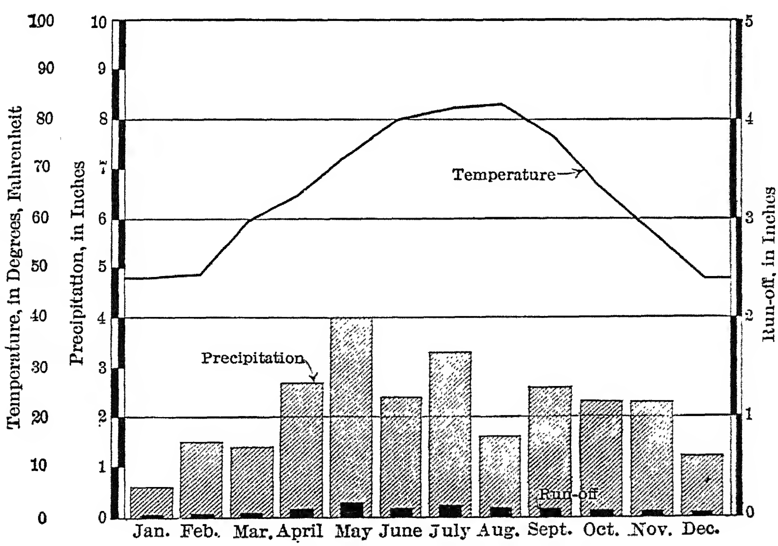


FIG. 191. — Temperature, Precipitation and Runoff, Colorado River Watershed, Austin, Texas, 1901–1910. Area, 37,000 sq. mi.

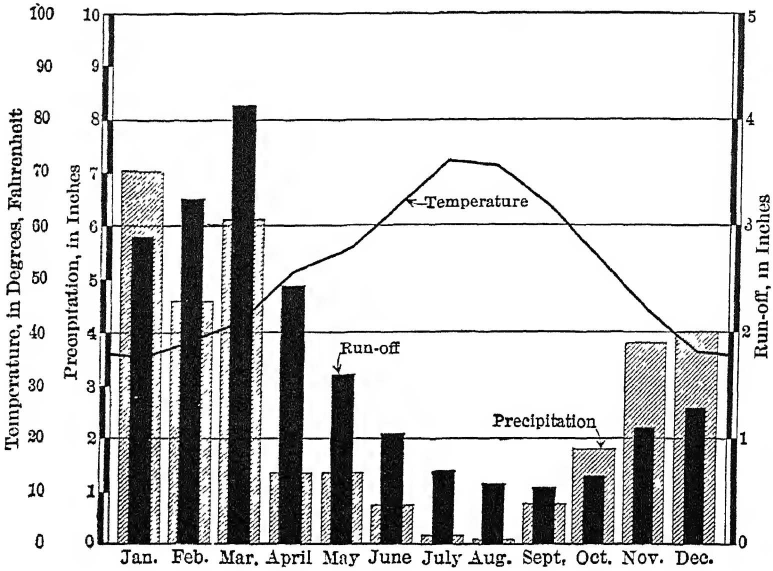


FIG. 192. — Temperature, Precipitation and Runoff, Sacramento River Watershed, Red Bluff, Cal., 1902–1911. Area, 10,400 sq. mi.

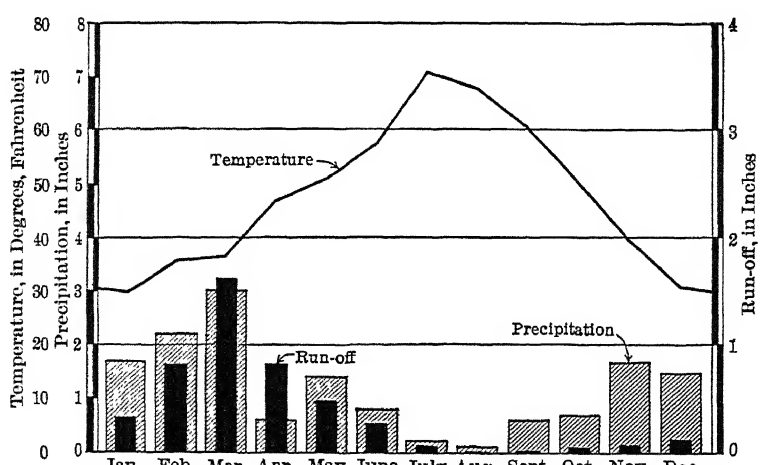


FIG. 193. — Temperature, Precipitation and Runoff, Pit River Watershed, Bieber, Cal., 1903–1908. Area, 2950 sq. mi.

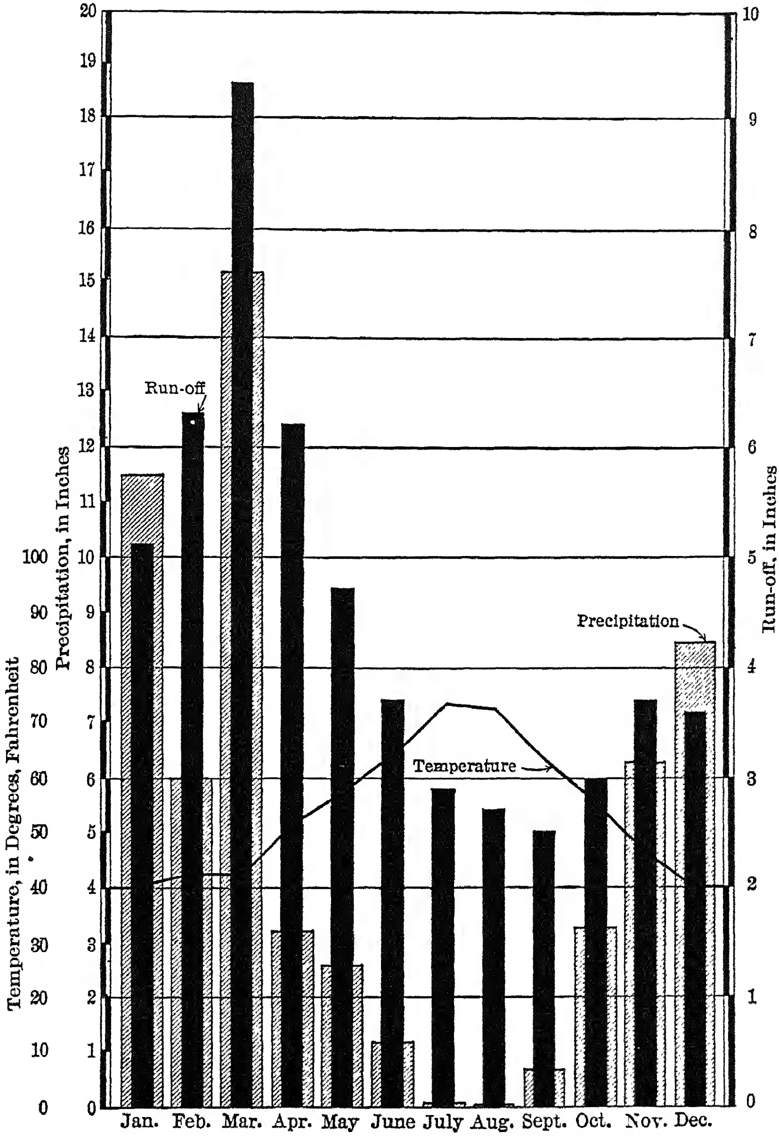


FIG. 194. — Temperature, Precipitation and Runoff, McCloud River Watershed, Gregory, Cal., 1902–1908. Area, 608 sq. mi.

Watersheds in the Northwest. — The Mississippi River, Minnesota, and the St. Croix River, Wisconsin, watersheds are typical of those in the Northwest. They are characterized by great fluctuations in temperature and precipitation. A variation of nearly 60 degrees in monthly mean temperature is shown, with five months of the year averaging below freezing and midsummer temperatures reaching about 70 degrees. The precipitation during the five winter months amounts to only about 6 inches, most of which, however, accumulates as snow and ice. The precipitation during the seven summer months aggregates about 24 inches, most of which evaporates or is used by plants in transpiration. Winter stream flow is maintained almost entirely by ground-water.

Watersheds in the East. — The Ohio River, Tohickon Creek, Pennsylvania, and James River, Virginia, watersheds are characterized by relatively small variations in precipitation and with winter temperatures near or above the freezing point. Little of the winter precipitation accumulates and as the evaporation loss is small and the transpiration loss is zero, the winter runoff is high. During the summer months the relation between rainfall and runoff is not widely different from that shown by the watersheds of the Northwest. Lower precipitation on the Ohio River watershed during the fall results in less runoff than from the James and the Tohickon.

Southern Watersheds. — The Tombigbee, Mississippi, and Colorado River, Texas, watersheds are typical of a variety of southern watersheds. The Tombigbee River watershed shows relatively uniform distribution of precipitation. The Colorado River watershed shows a distribution somewhat similar to that in the Northwest. The effect of high temperatures, however, is clearly evident.

If the Minnesota precipitation occurred at Texas temperatures, the runoff from the upper Mississippi River watershed would be about the same as that shown for the Colorado; and if the Colorado precipitation occurred at Minnesota temperatures,

the runoff from the Colorado River watershed would be quite comparable to that now observed on the upper Mississippi.

The precipitation over the Colorado River watershed is relatively small and occurs during the warmer portion of the year. The temperature is so high the year around that most of the precipitation evaporates or is used by vegetation. Practically the entire runoff results from excessive rains over restricted areas. The water-table is far below the bed of the streams, so that seepage flow is substantially nil.

High summer and fall temperatures on the Tombigbee River watershed together with high transpiration loss from the heavily forested area, result in very low summer and fall runoff. Soil storage having been depleted, the fall rains are mainly absorbed, resulting in low stream flow until well into the winter.

Western Watersheds. — The Sacramento River and its tributaries, the Pit and the McCloud, are typical western streams. The precipitation on these watersheds is very unequally distributed. By far the greater portion occurs during the cooler months. Other conditions being equal, watersheds on which the precipitation is distributed as shown for the Sacramento River suffer the least possible evaporation and transpiration losses. Those on which the precipitation is distributed as on the Tohickon Creek watershed suffer a greater loss, and those on which the precipitation is distributed as on the upper Mississippi watershed show by far the greatest loss of water through evaporation and transpiration.

The Sacramento River also shows the effects of melting snows in the mountains, in maintaining stream flow during the dry season. The high summer flow of its snow and spring-fed mountain tributary, the McCloud, is particularly prominent.

The temperatures shown for the McCloud River watershed are undoubtedly higher, and the precipitation somewhat lower, than the true average for the watershed on account of the fact that a considerable portion of the drainage basin consists of

mountain peaks higher in elevation than the highest meteorological observation stations for which records were available.

The Pit River watershed has very low precipitation but a reasonably good runoff on account of the greater portion of the precipitation occurring during the winter when the temperature ranges around the freezing point. The physical characteristics of the above-mentioned watersheds are given on pp. 1103 to 1109, Trans. Am. Soc. C. E., Vol. LXXIX (1915).

Hydrographs of Daily Discharge. — While monthly mean values of runoff, such as those given in Figs. 185 to 194, convey considerable information relative to the interdependence of the two principal factors modifying the amount of water which different watersheds yield as runoff, namely precipitation and temperature, hydrographs showing the daily discharge of streams, alone, can demonstrate the effect of watershed characteristics. Such hydrographs of typical streams are shown in Figs. 195 to 203. The location of the watersheds of these streams is shown in Fig. 204. So far as possible, streams draining watersheds having about the same mean annual precipitation and temperature have been selected, so that differences in precipitation and temperature might not veil the effects of the physical characteristics of the different watersheds. Figs. 195 to 203 bring prominently to one's attention the tremendous diversity of stream flow represented by this group of watersheds chosen from such a restricted area as Minnesota and western Wisconsin. By selecting streams from different parts of the United States a still greater diversity of flow could, of course, be shown. None of the streams for which hydrographs are presented in Figs. 195 to 203 are located in a region of high precipitation. None of them drain rugged, mountainous territory; neither are any of them snow or glacier fed.

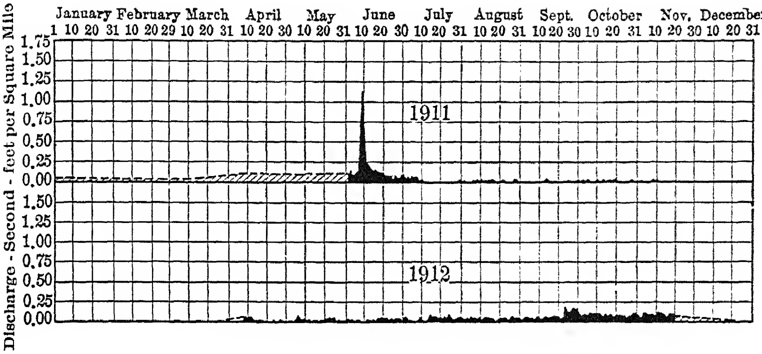


FIG. 195. — Hydrographs of Daily Discharge.
Red Lake River at Thief River Falls, Minn. (Below mouth of Thief River.)

Watershed area, 3430 square miles. Topography flat; 15% to 20% of it lake area. Largest lake in upper portion of watershed. Clay loam soil with clay subsoil. Dense timber, mostly coniferous, over eastern three quarters of watershed and prairie, much of it open marsh over remainder. Little land under cultivation. About three fourths of the watershed is swamp or lake area. Annual rainfall: mean, 24 in.; 1911, 20 in.; 1912, 19 in.

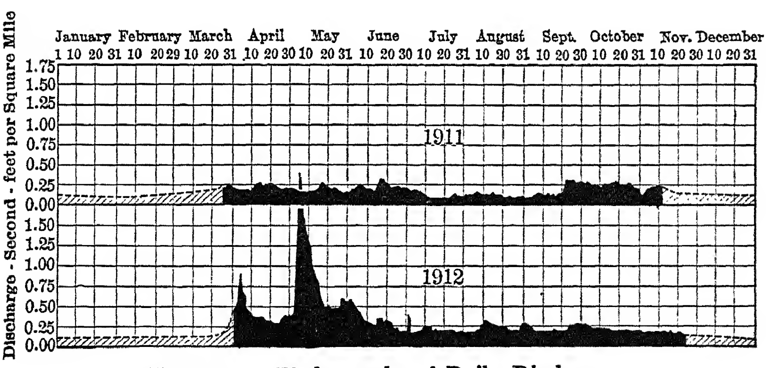


FIG. 196. — Hydrographs of Daily Discharge.
Crow Wing River at Pillager, Minn. (including Long Prairie).

Watershed area, 3230 square miles. Topography gently undulating; about 2% lake area and practically no swamp. Sand, gravel and clay soil. Dense, coniferous forests over upper portion and less dense over most of the remainder, with some land under cultivation in southern portion of basin. Most of watershed logged over, but second growth dense. Annual rainfall: mean, 26 in.; 1911, 25 in.; 1912, 22 in.

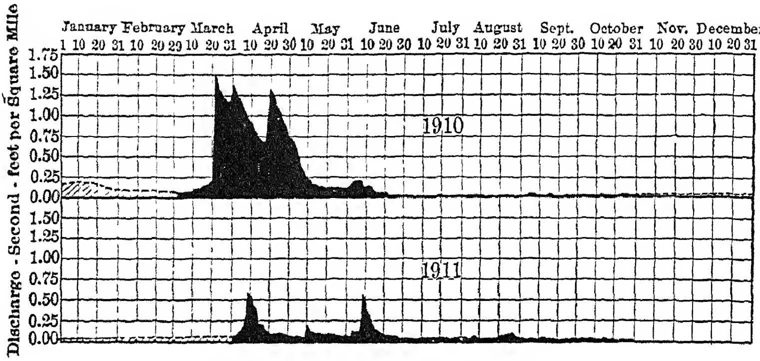


Fig. 197. — Hydrographs of Daily Discharge.
Clearwater River at Red Lake Falls, Minn.

Watershed area, 1310 square miles. Topography flat; less than 1% lake area. Soil clay loam with clay subsoil. Little cultivated land. Dense timber, mostly coniferous, over eastern two thirds of watershed and prairie with much marsh land over western one third. Estimated general slope about 3 ft. per mile. Annual rainfall: mean, 24 in.; 1910, 13 in.; 1911, 20 in.

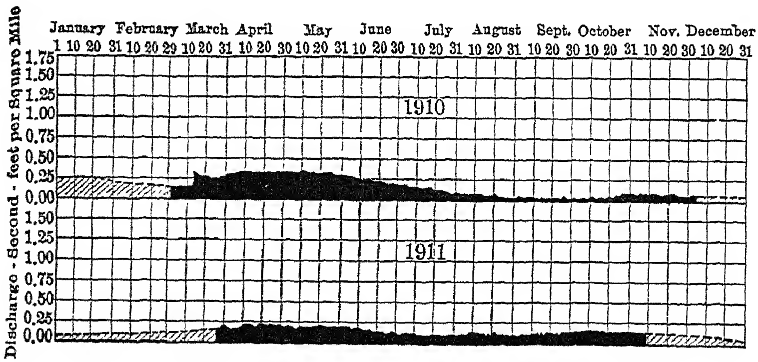


Fig. 198. — Hydrographs of Daily Discharge.
Ottertail River at Fergus Falls, Minn.

Watershed area, 1310 square miles. Topography prominently rolling, morainic, and knolly. About 15% lake area. Largest lake in lower portion of watershed. Soil varying from clay to sand and gravel. Upper portion of watershed lightly timbered. Southern portion largely under cultivation. Annual rainfall: mean, 25 in.; 1910, 14 in.; 1911, 24 in.

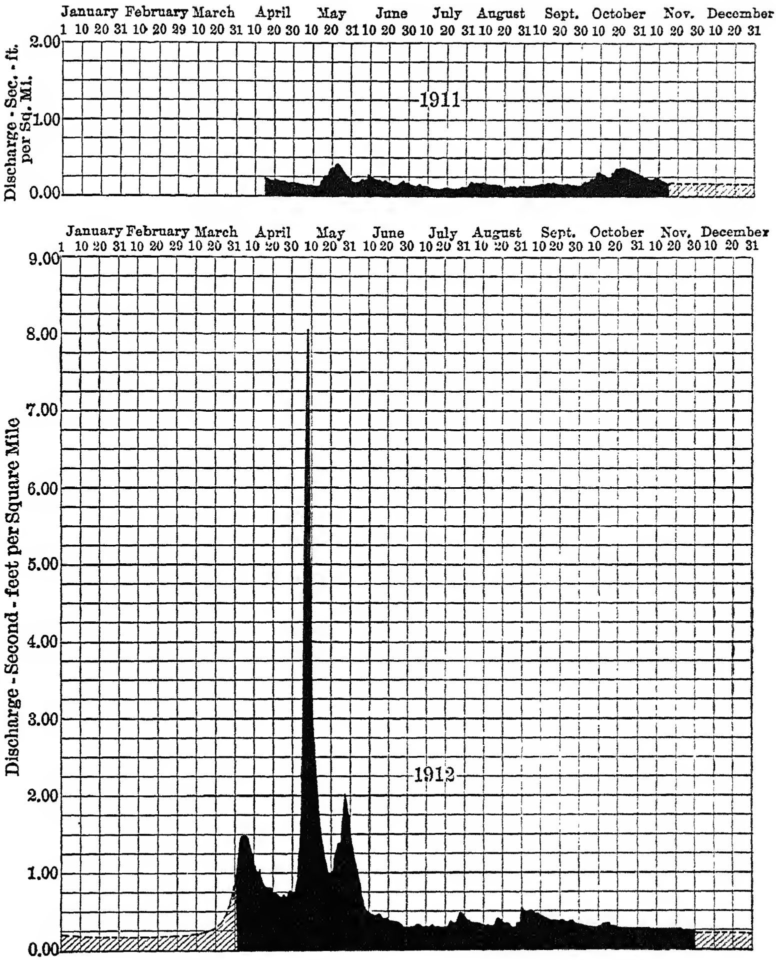


FIG. 199. — Hydrographs of Daily Discharge.
Elk River near Big Lake, Minn.

Watershed area, 615 square miles. Topography flat to gently rolling with occasional sand and gravel hills and less than 1% lake area. Soil black loam often quite sandy, with clay, sand, and gravel subsoil. Nearly all land under cultivation. Annual rainfall: mean, 28 in.; 1911, 32 in.; 1912, 29 in.

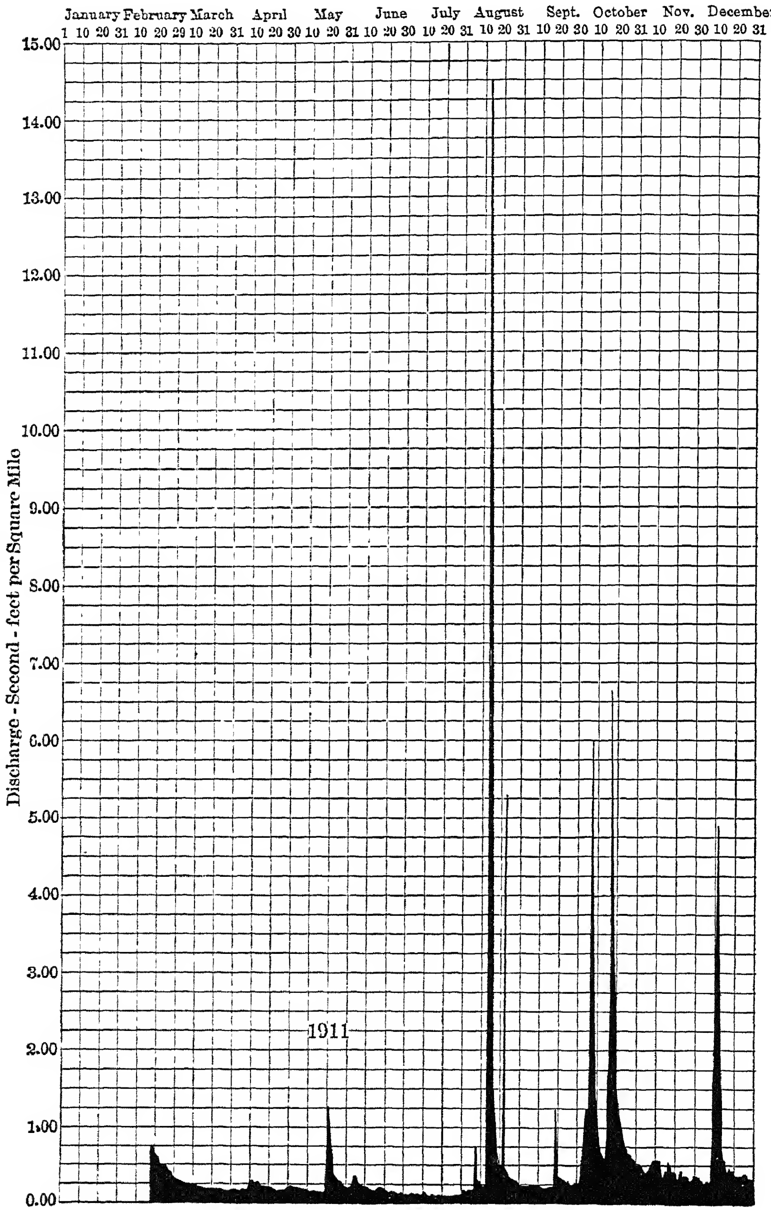


FIG. 200. — Hydrographs of Daily Discharge.
Root River at Lanesboro, Minn.

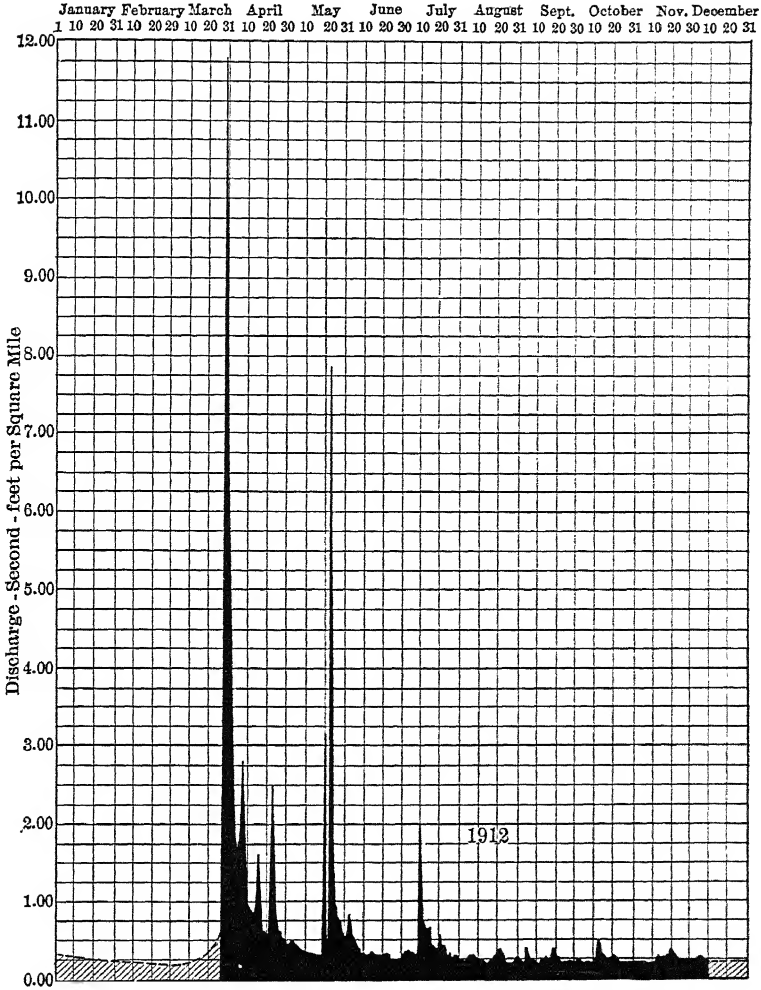


FIG. 201. — Hydrographs of Daily Discharge.
Root River at Lanesboro, Minn.

Watershed area 647 square miles. Topography relatively flat to gently undulating but streams flow through wide, deep, V-shaped valleys; that of main stream being several miles in width and several hundred feet below general level of surrounding country. No lakes. Soil clayey loam with clay subsoil and water-table far below surface of ground. Underlying sandstone rocks outcrop in river bed. Average slope of stream about 8 ft. per mile. Annual rainfall; mean, 30 in.; 1911, 45 in.; 1912, 30 in.

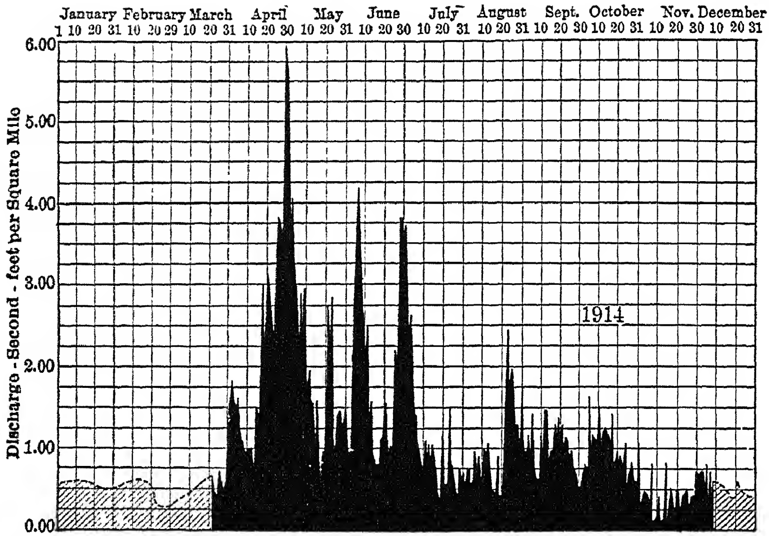


FIG. 202. — Hydrographs of Daily Discharge.
Wisconsin River between Rhinelander and Merrill.

Watershed area, 1520 square miles. Topography rolling with considerable number of lakes; about 5% of watershed under reservoir control. Soil quite sandy. Considerable land under cultivation; remainder covered with second growth. About half of land was burned over in 1909 to 1913. Most of lakes at upper end of streams. Annual rainfall: mean, 32 in.; 1914, 34 in.

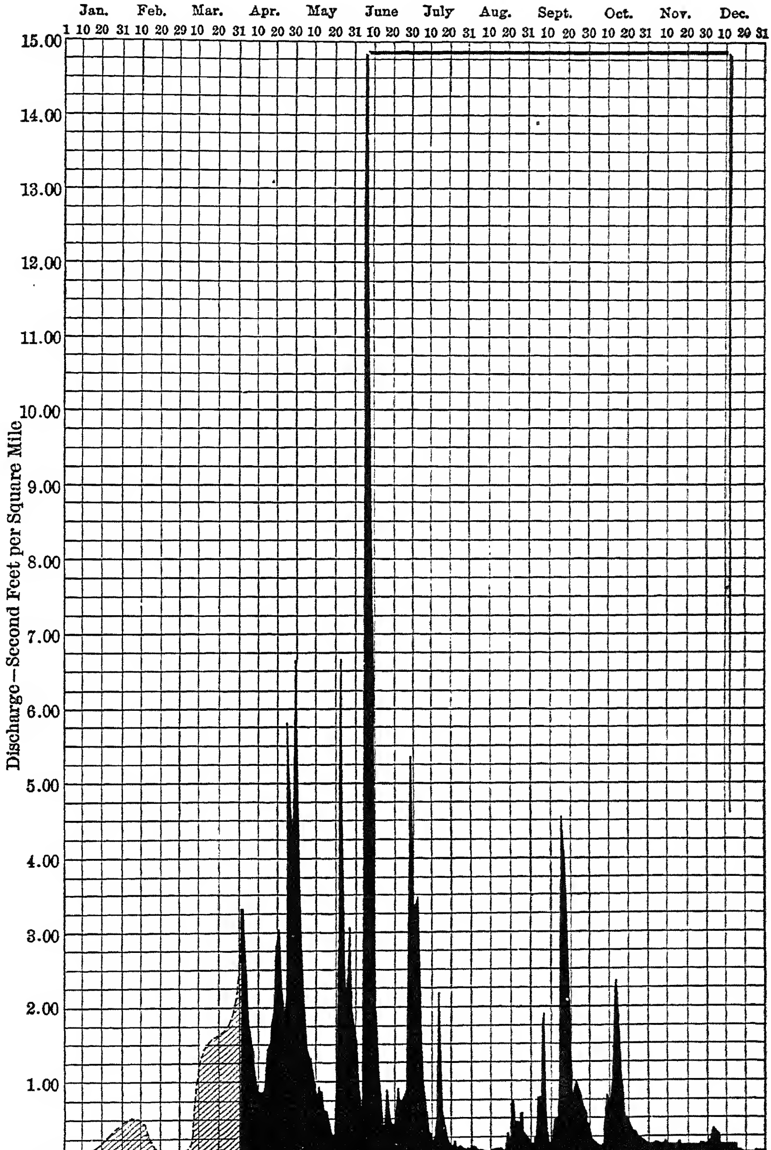


FIG. 203.—Hydrographs of Daily Discharge.
Black River at Neillsville, Wis. (1914).

Watershed area, 772 square miles. Topography distinctly rolling with no lake area. Soil rather clayey. Considerable land under cultivation. Timber mostly second growth. Streams in narrow V-shaped valleys. Average slope along stream about 6 ft. per mile. Annual rainfall: mean, 33 in.; 1914, 38 in.

The watershed characteristics essential to an interpretation of these hydrographs are briefly summarized under each figure. Both the Red Lake and the Clearwater Rivers drain large swamp areas. While these swamps have a tendency to equalize the stream flow, to some extent, their principal effect is to so increase evaporation and transpiration losses as to greatly reduce the total amount of runoff. Heavy precipitation on the Clearwater River watershed during 1909 and in the spring of 1910 resulted in heavy runoff during the 1910 break-up. Light precipitation during the remainder of 1910 and during 1911 resulted in very low runoff during that period.

The fact that sandy soils and lakes, in more rolling country, not only equalize stream flow, but conserve the rainfall far better than timbered swamps and marshes is clearly shown by comparing the discharge of the Red Lake and the Clearwater Rivers with that of the Crow Wing and the Ottertail, respectively. The watersheds of these streams are almost exactly equal in size, yet show a most striking diversity of flow. After the freeze-up in November, 1911, the discharge from the Red Lake watershed dropped to between five and ten cubic feet per second and remained so throughout the entire winter. For two entire years, from September, 1910, to August, 1912, the principal tributary of the Red Lake, *i.e.*, the Thief River, with a tributary watershed of over 1000 square miles, most of which is swamp and much densely timbered, yielded a total runoff of only .11 inch in depth over the watershed.

The June, 1911, freshet on the Red Lake River resulted from about 4 inches of precipitation during the month. The May, 1912, freshet on the Crow Wing River resulted from about 6.5 inches of precipitation during that month.

The Elk and the Root River watersheds are quite similar in surface topography. The differences shown by the hydrographs result mainly from the more sandy character of the soil on the Elk River watershed.

The rainfall on the Root River watershed in 1911 was very

much heavier than on the Elk. The 1912 precipitation was very nearly the same on both watersheds. The precipitation which caused the freshet of May, 1912, on the Elk River, shown in Fig. 214, was almost as large as that which caused the August, 1911, flood on the Root River, shown in Fig. 215. The March-April, 1912, break-up was not accompanied by heavy rains on either watershed. The small rise on the Elk River is, to a large extent, due to lesser soil and subsoil storage as indicated by the lower winter flow. Both streams show an exceptionally well sustained low-water flow.

While the Wisconsin River watershed between Merrill and Rhinelander is about twice as large as the Black River watershed at Neillsville, and would, therefore, be expected to show slightly less sudden fluctuations in stream flow, nevertheless, the differences shown result, primarily, from the more sandy character of the soil on the Wisconsin River watershed and the steeper slopes on the Black River. The regimen of these streams is somewhat similar to that of the Elk River and the Root River, respectively, although the Root River has a better low-water flow on account of the underlying sandstone rock that outcrops in the river bed.

The extraordinary flood on the Black River, in June, 1914, resulted from very exceptional precipitation (see Fig. 212) averaging 3.92 inches in 24 hours. In July, 1912, a precipitation of 5.15 inches in 24 hours produced a flood flow of 27.5 c.f.s. per square mile from the Wisconsin River watershed between Rhinelander and Merrill. A map of the rainfall causing this flood is shown in Fig. 213.

THE MIAMI RUNOFF STUDIES

The Miami Conservancy District* has recently made instructive experiments on runoff from small plats 5 feet square. The soil was a sandy loam for about 2 feet, underlain by sand and

* Miami Conservancy District, Technical Reports, Part VIII, 1921, by Ivan E. Houk.

gravel. The upper foot contained considerable humus. Only about 35 per cent of the upper 2 feet of soil was as fine as silt, or finer; the remainder was sand and gravel. The conclusions drawn from these studies are condensed into 24 paragraphs from which the following have been selected, with some comments, by the author.

> "1. That the surface soil, which extends only to a depth of about 2 feet, weighs about 100 pounds per cubic foot, in place, when dry."

A weight of 100 pounds per cubic foot is representative of sand, with 40 per cent voids.

> "2. That the soil when saturated contains an amount of moisture equal to about 41 per cent of the volume, or about 25 per cent of the dry weight of the soil."

A moisture-holding capacity of 41 per cent of its volume is equivalent to a total capacity for water of 4.9 inches per foot depth. This agrees exactly with the author's diagram on page 270.

> "3. That during the dryest times of the summer the 2-foot depth of soil never contains less than from 3 to 4 per cent of moisture, by weight."
>
> "4. That the moisture-holding capacity of the 2-foot layer of soil is about 21 per cent by weight."

This apparently refers to the capacity for "gravity water" and represents about 3.4 inches per foot. This corresponds to a soil between sand and silt on the author's diagram on page 270.

> "7. That the upper 2 feet of soil seldom, if ever, becomes filled with capillary water during the months of June, July, or August, even though the rainfall is considerably greater than normal."
>
> "9. That during the summer, rates of evaporation from bare soil and of transpiration and evaporation from sod surfaces, may be as great as a half an inch per day for periods as long as five days."
>
> "11. That the average rate of evaporation from snow surfaces during the period from December 3, 1917, to February 11, 1918, was about 0.023 inch per day."

This corresponds to the evaporation from snow given by the author's Fig. 150, page 235, for a temperature of 21 de-

grees. The mean temperature during the experiment was 19 degrees.

> "12. That the actual amount of moisture in the upper 2 feet of soil is equivalent to a depth of about 1.5 inches when the soil is dryest, and to a depth of about 8 inches when the soil contains the maximum amount of capillary water, the difference in the two amounts being about 6.5 inches."

"Capillary water" in this conclusion undoubtedly represents "gravity water" in the author's Fig. 169 (*b*). For the soil of the experiments this figure shows "capillary water" plus "hygroscopic water" of 1.5 inches per foot and "gravity water" of 3.3 inches per foot. This shows excellent agreement.

> "14. That the amount of water absorbed by the upper 2 feet during individual storms was greatest during the storm of August 4 to 8, 1916, amounting to about 4.0 inches, the total precipitation being 4.56 inches."
>
> "15. That the amount of water absorbed by the upper 2 feet during a given storm is greater under sod surfaces than under bare soil surfaces."
>
> "17. That appreciable surface runoff frequently occurs during intense summer storms when the upper 6 inches of soil are not nearly saturated."
>
> "18. That surface runoff does not occur during some less intense storms even though the ground is saturated."
>
> "19. That water can percolate through the 2-foot layer of surface soil on the bare soil plats at Moraine Park, when the ground is saturated but not frozen, at a rate as great as 0.25 of an inch per hour."
>
> "20. That water can be absorbed by the bare soil at times when the soil is unusually dry, at a rate as great as 1.00 inch per hour for intervals as long as 30 minutes."
>
> "21. That water cannot be absorbed by the bare soil at any time, no matter how dry it is, at a rate as great as 3.00 inches per hour for periods as long as 5 minutes."

THE FLOOD FLOW OF STREAMS

Most streams of the country are subject to considerable variation in stage. Under normal conditions the discharge is carried within well-defined banks but, periodically, most streams experience a runoff from the tributary watershed which is greater than can be carried at a bank-full stage. At such times the

stream leaves its banks and spreads out over its valley. As a river usually carries considerable detritus in times of flood and as the shallower water outside of the banks has a slower velocity than that within the banks, the sediment is deposited, forming the well-known alluvial flood plain. The very presence of such a flood plain is conclusive evidence of prevalent floods.

In the development of the country, however, many people have too often associated such physiographic features as this with ancient geologic ages and have attempted to occupy the river's flood plain, only to find their structures destroyed and their fields laid waste. The fertility of the alluvial valley and its accessibility through the river channel, when other means of communication were wanting, coupled with the relatively infrequent occurrence of devastating floods and the optimism of flood sufferers, have been irresistible inducements to occupation.

Floods Due to Rainfall

Flood Producing Rains. — As floods originate in precipitation, its amount and distribution are of primary importance. Floods may result from either rainfall, snowfall, or a combination of the two.

Flood producing rains are not limited to regions of high annual precipitation; in fact, torrential rains, though less frequent, are, nevertheless, common in the arid and semi-arid West. The smaller the watershed tributary to a stream, the more intense and concentrated the precipitation required to produce a flood stage. Protracted general rains, that produce only moderate stages in the minor water courses, cause floods on the main stream. Torrential rains, commonly called "cloud-bursts," that have little effect on the main stream, cause floods on its tributaries. In general, the maximum flood due to rain will result from the greatest amount of most unfavorably distributed precipitation which may be expected to occur over

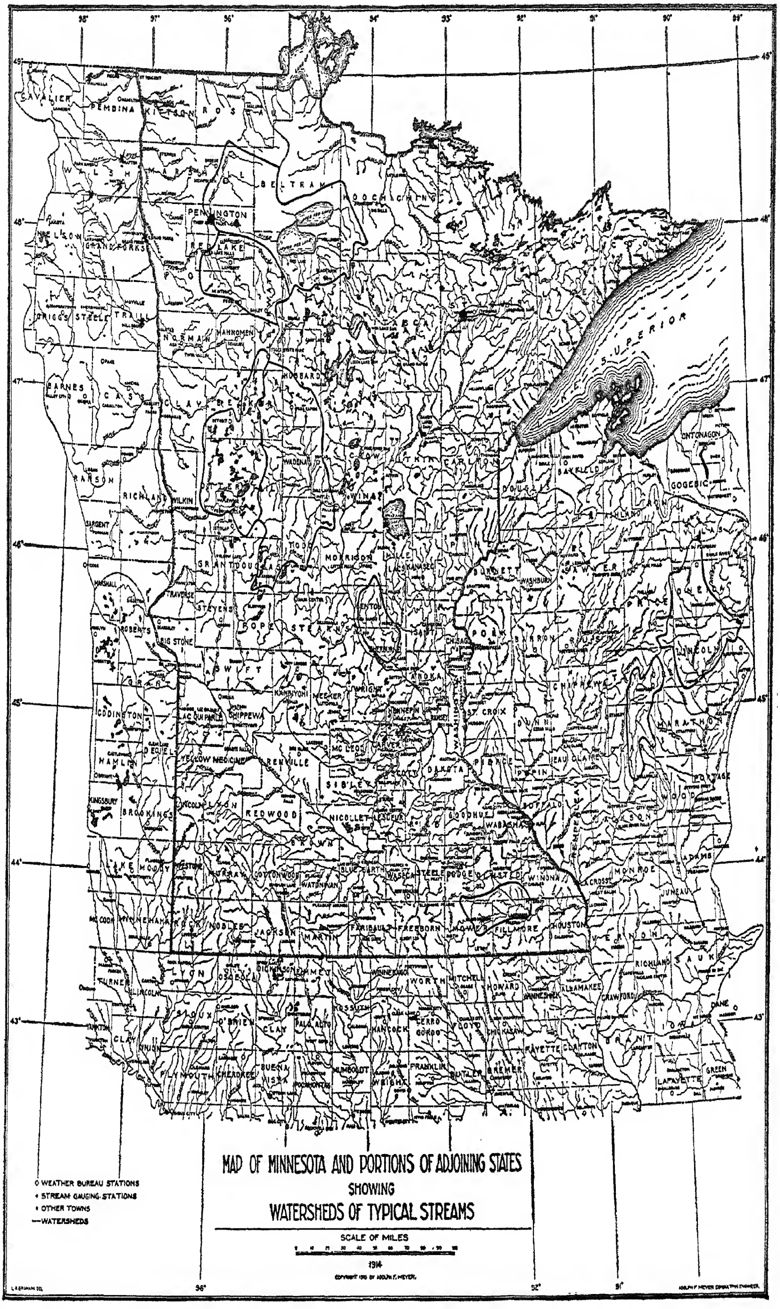

MAP OF MINNESOTA AND PORTIONS OF ADJOINING STATES
SHOWING
WATERSHEDS OF TYPICAL STREAMS
O WEATHER BUREAU STATIONS
+ STREAM GAUGING STATIONS
• OTHER TOWNS
— WATERSHEDS
SCALE OF MILES
1914

Fig. 204.

the entire tributary watershed within the time required for water from the remotest portion of the drainage basin to reach the point of observation. The time of concentration, in turn, depends upon the topography of the watershed and the size and slope of the water course.

Intense Rainstorms as Basis for Flood Estimates. — Records of runoff will, for a good many years, be far more incomplete, in most parts of the United States, than records of rainfall. By making a thorough analysis of all available rainfall and runoff data, a better judgment can be formed of the probable extreme flood flow of a given stream, than if observed streamflow data, alone, are relied upon. A study of the most intense rainstorms in the part of the country under investigation should first be made. The measure of intensity of storms must include both watershed area and average precipitation over that area, together with its distribution. The rainfall which caused the greatest recorded flood on the given stream should then be mapped and studied in connection with the resulting flood discharge. A comparison of the given rainstorm with the most intense storm to be expected within the locality under consideration will then afford a basis for estimating the probable extreme future flood. The frequency of occurrence of extreme floods, however, must remain a matter of uncertainty until very much more data are available.

Effect of Watershed Area. — Perhaps the most important single factor influencing the flood flow of a stream is the size of its tributary watershed. The reason lies in the variation of precipitation with area. Torrential rains aggregating five to ten inches in a day, or less, occur only over relatively small areas, because the available moisture supply of the air on a summer day, if uniformly precipitated over the entire continent, would amount to very much less than this. Excessive precipitation over a small drainage basin is possible only at the expense of precipitation on the adjoining watersheds. So pronounced is the effect of watershed area on flood flow, that widely

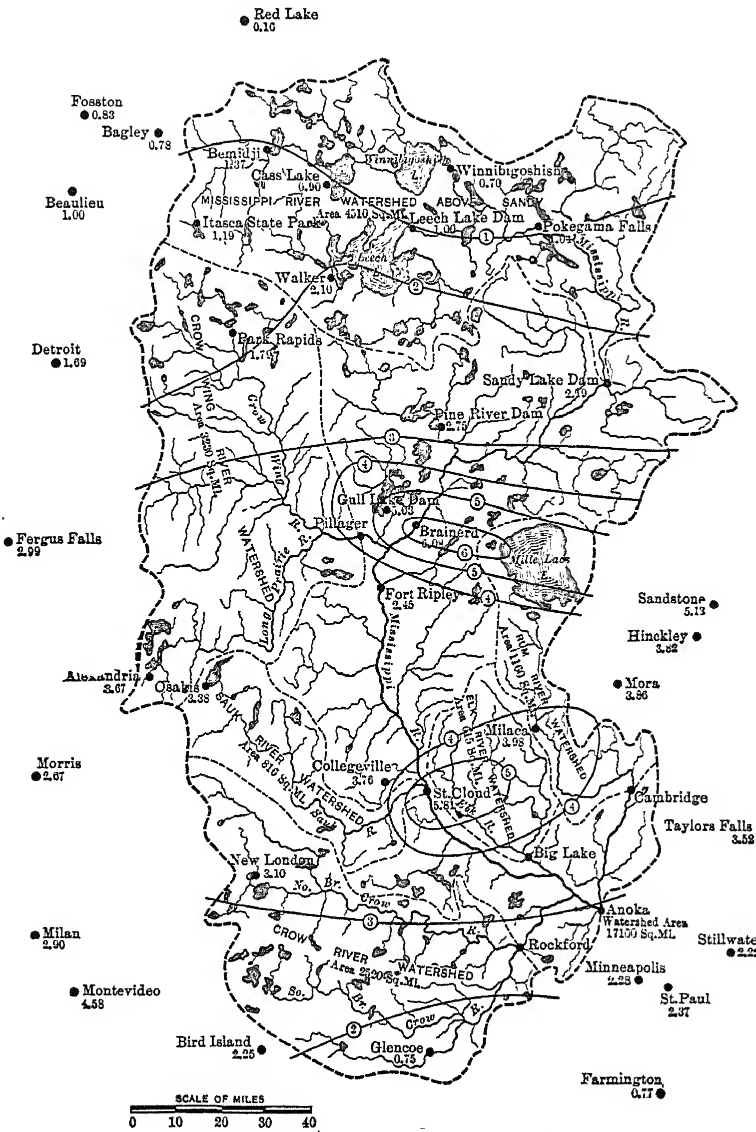
scattered watersheds of equal area but of dissimilar topographical characteristics experience quite similar flood flows.

Differences in precipitation over a large watershed result in irregularities in stream flow on the tributaries that are completely smoothed out when the main stream is reached. This is well shown by the hydrographs, Fig. 205, of the Mississippi River at Anoka, Minnesota, and of its principal tributaries.

Reasonably heavy, but irregularly distributed rains occurred on the watershed between May 3 and 5 as shown in Fig. 206. As a result of these rains a flood of somewhat more than ordinary magnitude for the main stream crested at Anoka, Minnesota, on May 8. None of the large tributaries, except the Elk and the Rum rivers, experienced more than an ordinary flood. The time of cresting of this flood at Anoka seems to have been determined mainly by the discharge of the Elk and the Rum rivers and of the minor tributaries aggregating about 35 per cent of the total watershed area.

Of the larger tributaries, the Crow Wing crested before the main stream, and the Sauk and Crow rivers crested after it, and thus prolonged the flood, although they did not increase it. The effect of the upper Mississippi reservoirs is well shown by the uniform discharge of the main stream just below the four main reservoirs, and by a comparison of the hydrograph showing the runoff from the entire watershed above Anoka with that from the watershed *below* the reservoirs.

Effect of Shape and Location of Watershed. —A fan-shaped drainage area that permits the water from several equal-sized tributaries to reach the main stream at the same time, and an elongated area draining in the direction the storm moves will, in general, experience more serious floods than more irregularly shaped areas. Most streams like the Ohio draining in the opposite direction from that in which the storm moves, have far less severe floods than if they drained in the other direction. Streams draining to the north have more severe spring floods than those draining to the south on account of the gorging of the lower,



WATERSHED OF MISSISSIPPI RIVER
AND ITS PRINCIPAL TRIBUTARIES
ABOVE ANOKA, MINNESOTA
WITH ISOHYETALS FOR MAY 3-5, 1912

FIG. 206.

frozen-up reaches of the stream, with water running off from the warmer, more southerly portion of the drainage basin. This is well illustrated by the Red River of the North.

Effect of Soil. — Clay soil or rock outcrops and steep slopes result in the rapid concentration of flood waters. Pervious soil and flat slopes give the floods of a stream draining a small watershed many of the characteristics of one draining a much larger area. This is illustrated by the Crow Wing River watershed.

Effect of Cultural Conditions. — When flood producing rains fall on a watershed, cultural conditions, such as forest cover, have little effect in retarding the flow. At best, they are of secondary importance. Forests may contribute to floods by retarding the melting of snow as illustrated by the Little Fork River watershed.

Watershed Characteristics Reflected in Floods. — Differences in watershed characteristics are prominently reflected in the flood hydrographs of the Root, Elk, Black, Wisconsin and Wild Rice rivers, Figs. 207 to 211. Of these five streams the Black River discharged the most water, although the rainfall on the watershed was least. The physical characteristics of the Black River watershed are given on page 325. The absorptive character of the Wisconsin River watershed, notwithstanding moderately steep slopes, is well shown by the hydrograph of that stream. Maps of the rainfall which caused the floods on the Black and the Wisconsin rivers are given in Figs. 212 and 213.

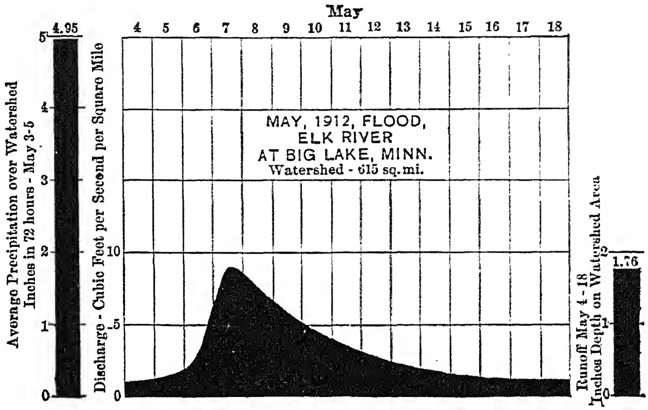


FIG. 207.

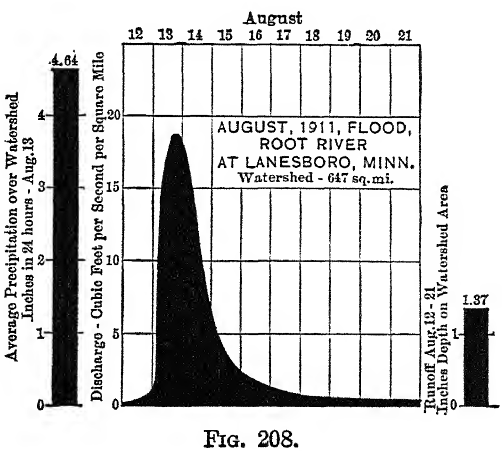


FIG. 208.

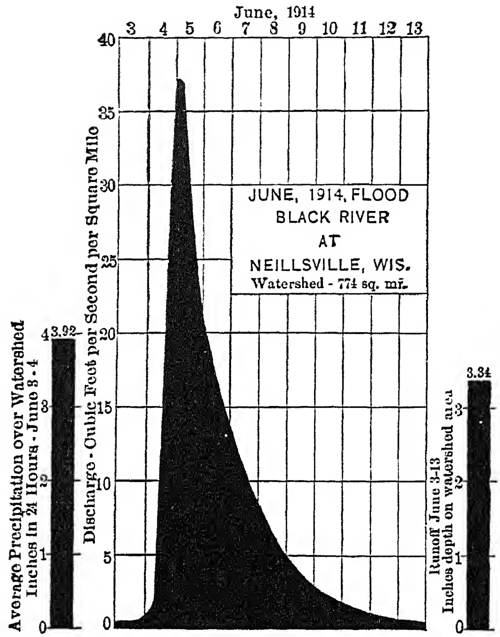


Fig. 209.

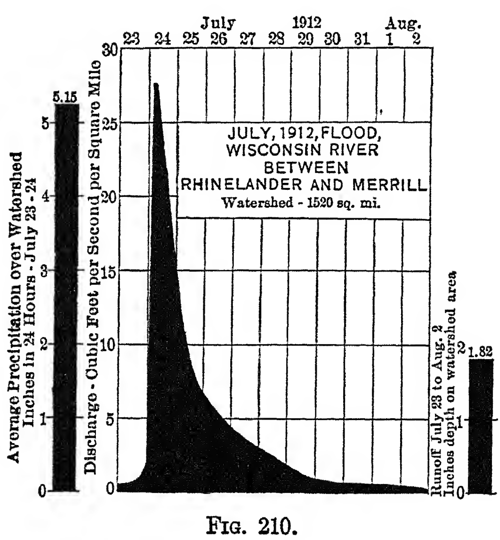
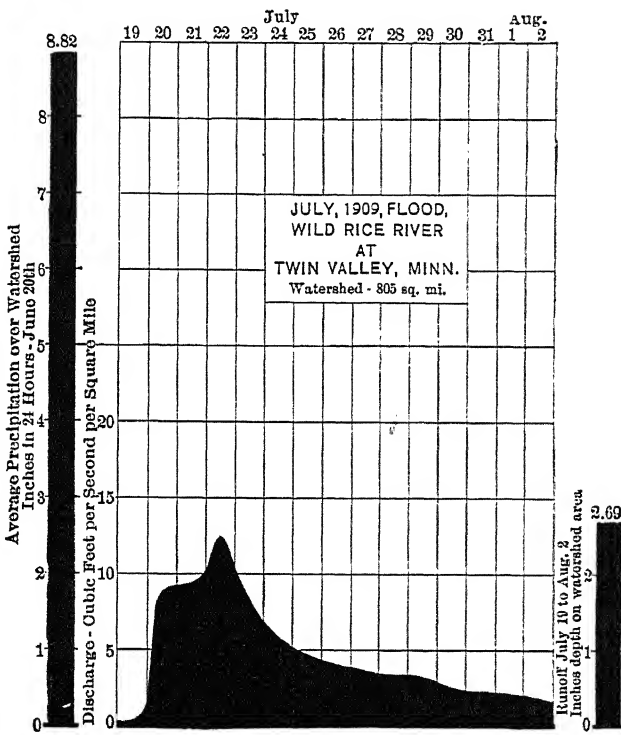


Fig. 210.



July
Aug.
19 20 21 22 23 24 25 26 27 28 29 30 31 1 2
8.82
8
7
6
5
4
3
2
1
0
Average Precipitation over Watershed
Inches in 24 Hours - June 20th
Discharge - Cubic Feet per Second per Square Mile
20
15
10
5
0
JULY, 1909, FLOOD,
WILD RICE RIVER
AT
TWIN VALLEY, MINN.
Watershed - 805 sq. mi.
Runoff July 19 to Aug. 2
Inches depth on watershed area
2.69
2
1
0

FIG. 211.

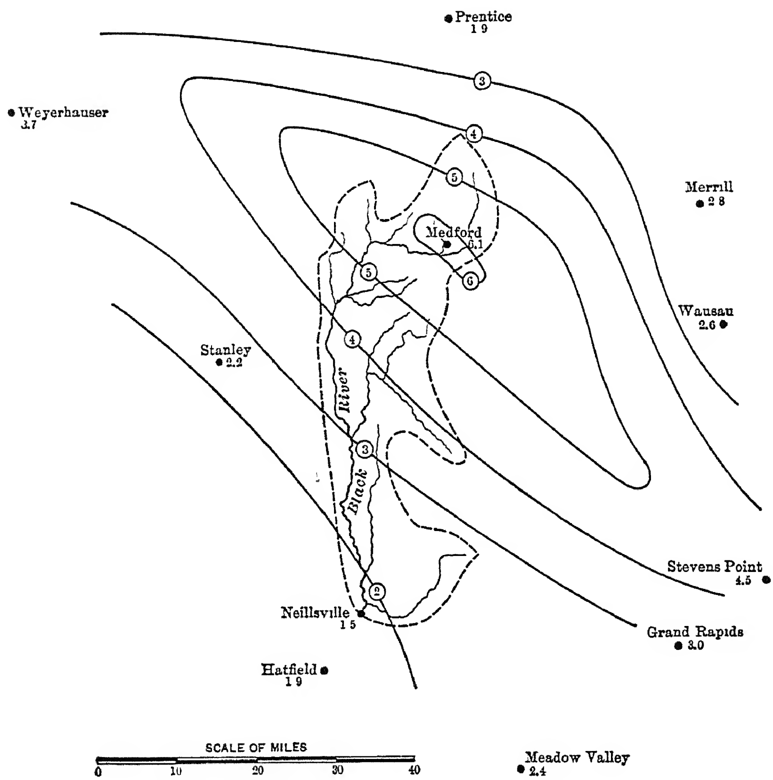


FIG. 212. — Medford, Wisconsin, Storm, Black River above Neillsville. June 3–4, 1914. One-day Storm.

Average precipitation over Black River Watershed above Neillsville, 3.92 in.

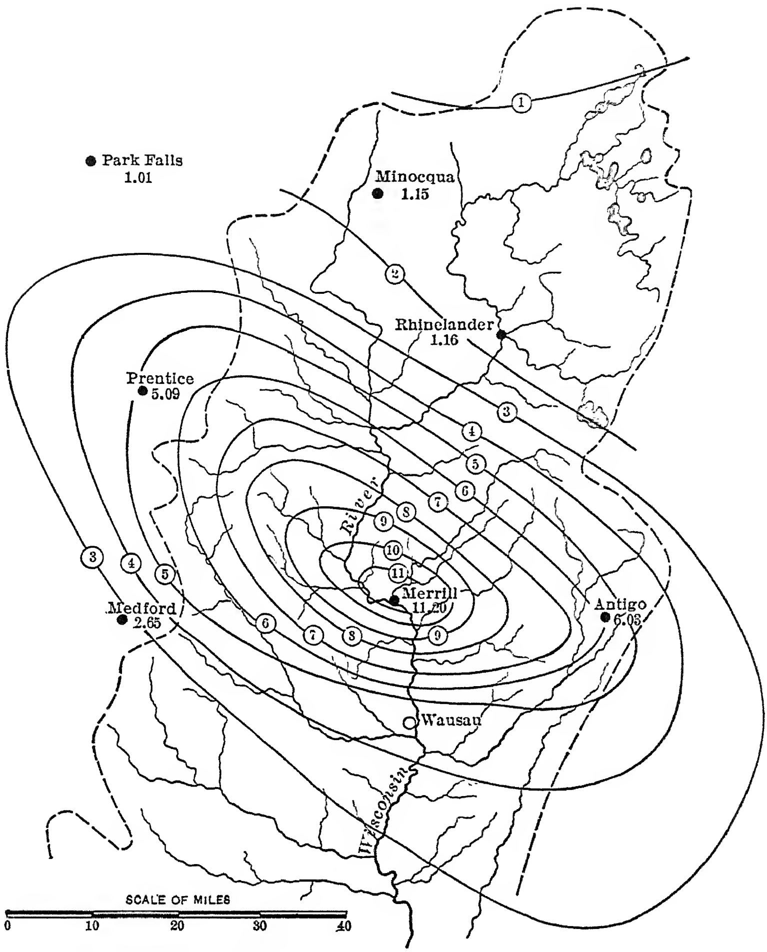


FIG. 213. — Merrill, Wisconsin, Storm, July 23–24, 1912. Less-than-one-day Storm.

Elk River Flood. — The May, 1912, Elk River flood shown in Fig. 207 resulted from 4.95 inches of rain over the watershed in three days. The physical characteristics of this watershed are given on page 321. The river had been moderately high throughout April and the ground was very moist; consequently there was heavy runoff, notwithstanding the normally large absorptive capacity of the soil of this watershed.

Root River Flood. — The Root River flood of August, 1911, Fig. 208, resulted from 4.64 inches of rain in 24 hours. The physical characteristics of this watershed are given on page 323. The river had been extremely low during July, but moderate

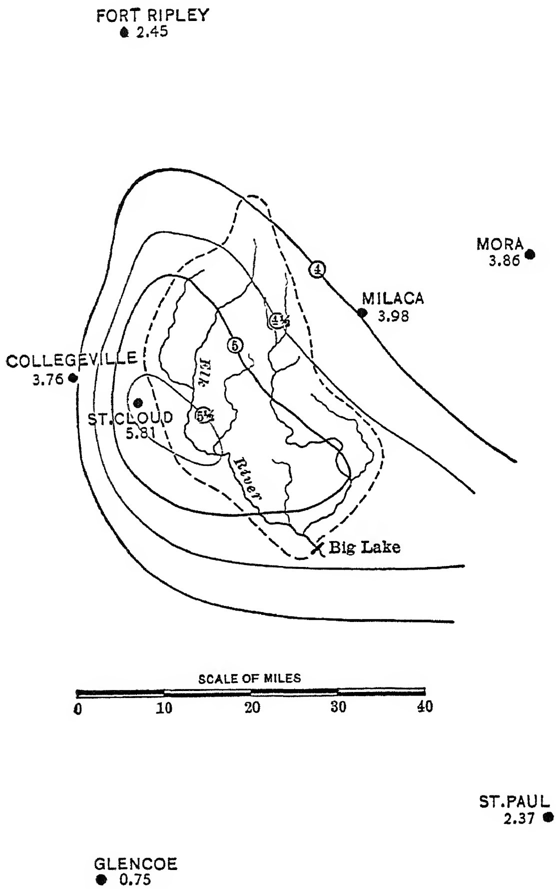


Fig. 214. — St. Cloud, Minnesota, Storm. May 3–5, 1912.

rains had fallen early in August so that the soil was in good condition to absorb the heavy rainfall of August 13. While the total runoff was relatively less than that from the Elk River watershed, the steeper slopes on the Root and the concentration

of the rainfall within 24 hours caused a much higher and sharper flood peak.

Maps of the rainfall causing these floods are given in Figs. 214 and 215.

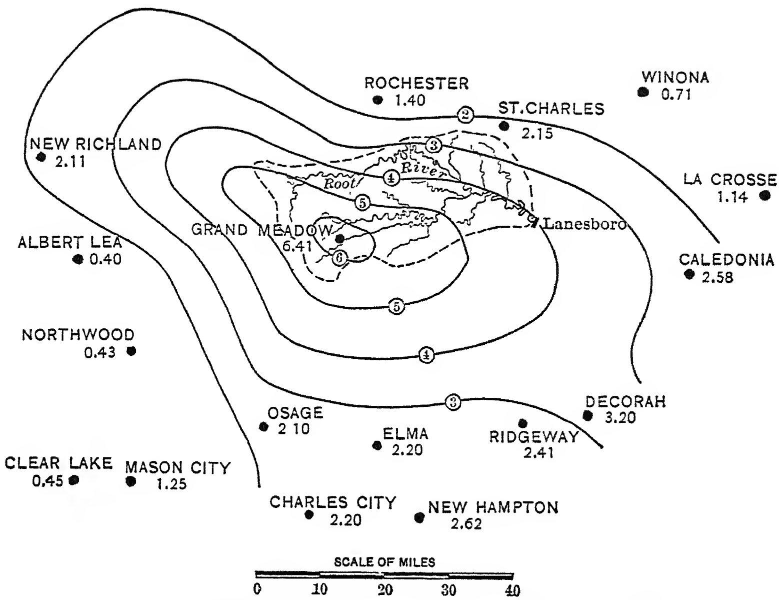


FIG. 215. — Grand Meadow, Minnesota, Storm, August 13, 1911. One-day Storm.

Wild Rice River Flood. — The storm that caused the flood on the Wild Rice River was the second severest recorded in the Northwest, so far as small watersheds are concerned. (See Fig. 123.) The greatest recorded storm in this region is that which centered at Fort Madison, Iowa, June 9 to 10, 1905. These two storms furnish a good basis for estimating the probable maximum flood flow from watersheds of the Northwest having an area of less than about 5000 square miles. While it is impossible to say with what frequency such intense rainstorms as these will probably occur on any given watershed, nevertheless, it is safe to say that since only two storms of the given intensity have occurred in the Northwest during the past twenty years,

notwithstanding the large number of stations at which the rainfall has been observed, such storms are not to be expected on any given watershed with a greater frequency than, perhaps, once in several hundred years.

The outstanding feature of the Wild Rice River flood, Fig. 211, is the small runoff which resulted from the extraordinary precipitation on the watershed. The explanation of this fact is to be found in the characteristics of the watershed. The slopes in the basin are very gentle. The topography varies from morainic to flat but there is very little swamp land. About 5 per cent of the basin is lake area. Many of these lakes have no outlet, their inflow evidently being lost largely by percolation. About 20 per cent of the drainage area is controlled by logging and other dams. Only the extreme upper part of the basin is heavily forested. The remainder consists of brush and open prairie, with considerable land under cultivation. The soil has good absorptive capacity. In the lower half of the basin artesian wells are found at depths of about 200 feet, in a stratum of sand and gravel overlain by clay. In the lower reaches of the main stream, several important tributaries become lost in the lowlands.

The river overflowed its banks at the gaging station during the flood of 1909, and the discharge record is probably considerably in error as the flow was computed by Kutter's formula.*

Scioto River Flood. — Fig. 216 shows the 1913 flood on the Scioto River at Columbus, Ohio. The rainfall which caused this flood is mapped in Fig. 217. The precipitation shown on this map is that which fell before the river had crested. It averaged 6.1 inches on the watershed. The total rainfall from March 23 to 31, *viz.*, 9.54 inches, is given on the flood hydrograph for the purpose of comparing it with the total runoff during the flood. The outstanding feature of the Scioto flood is the fact that about 90 per cent of the rainfall appeared

* Report of Water Resources Investigation of Minnesota, 1909 to 1912, p. 402.

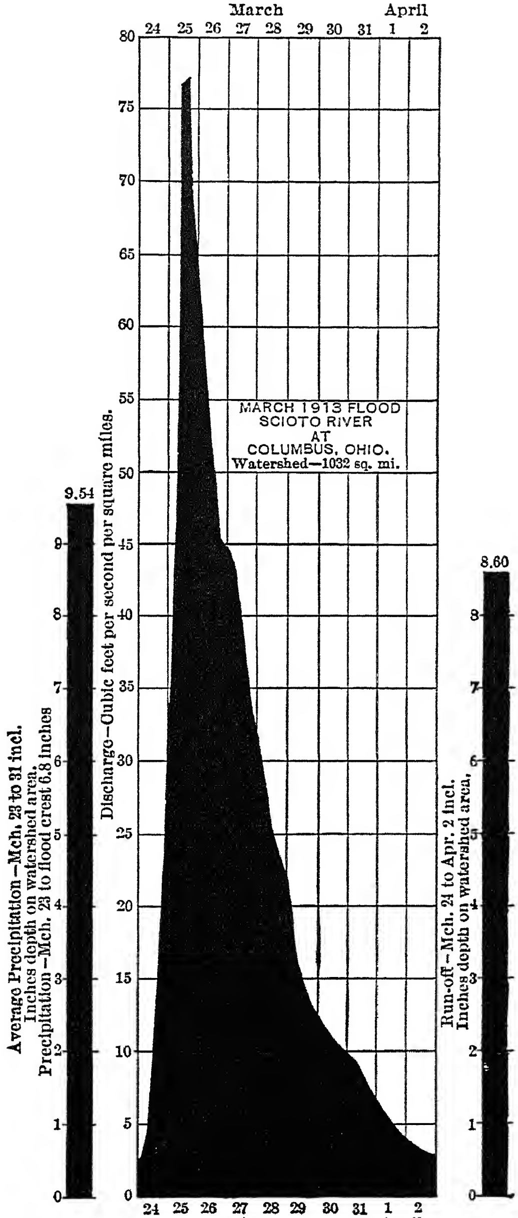

March
April
24 25 26 27 28 29 30 31 1 2
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
MARCH 1913 FLOOD
SCIOTO RIVER
AT
COLUMBUS, OHIO.
Watershed—1032 sq. mi.
Discharge—Cubic feet per second per square miles.
9.54
Average Precipitation—Mch. 23 to 31 incl.
Inches depth on watershed area.
Precipitation—Mch. 23 to flood crest 6.8 inches
8.60
Run-off—Mch. 24 to Apr. 2 incl.
Inches depth on watershed area.
24 25 26 27 28 29 30 31 1 2
March
April

FIG. 216.

in the stream. This is due to the steep slopes and the saturated condition of the ground when the rains began.*

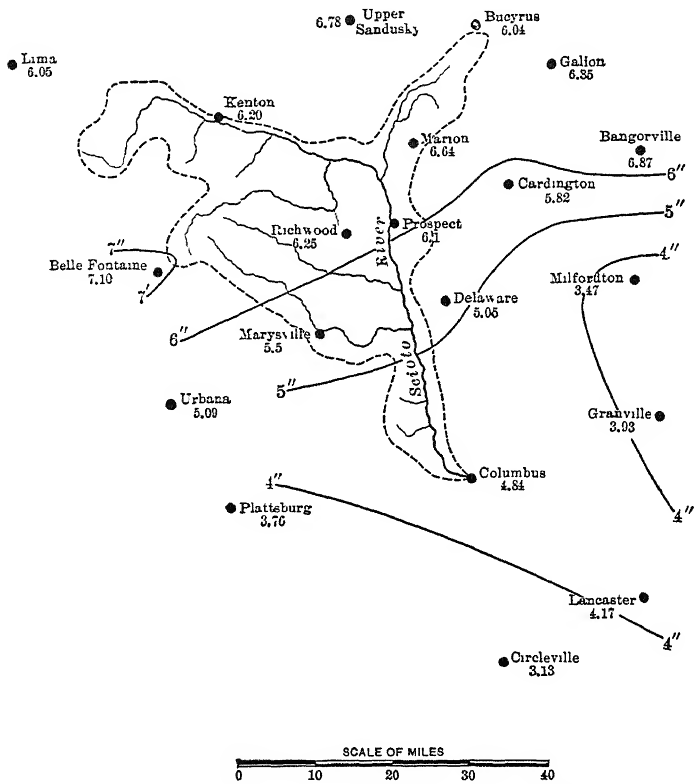


FIG. 217. — Central Ohio Storm, March 23 to 1 p.m. March 25, 1913. Two-and-one-half-day Storm.

Ohio River Flood. — Fig. 218 shows the 1913 flood on the Ohio River at Cincinnati. The peculiar shape of the hydrograph is due to the fact that the flood water of the Great Miami was the first to reach the Ohio, at Cincinnati. The current was either upstream, or imperceptible, for about 36 hours.† For

* Re Scioto Flood, see Report on Flood Protection for the City of Columbus, Ohio, by John W. Alvord and Charles B. Burdick, Sept. 15, 1913.

† See Bulletin Z of the U. S. Weather Bureau, "The Floods of 1913," pp. 25 and 26.

more than two days the gage height at Cincinnati was no indication, whatever, of the discharge of the stream. This is well shown by the hydrographs and the graph of fall between Maysville and Cincinnati, Fig. 219. Both the values of discharge given by the U. S. Geological Survey in Water Supply Paper No. 334, page 65, and the estimate made by the author, of the probable discharge of the stream, are shown on the flood hydrograph of Fig. 218.

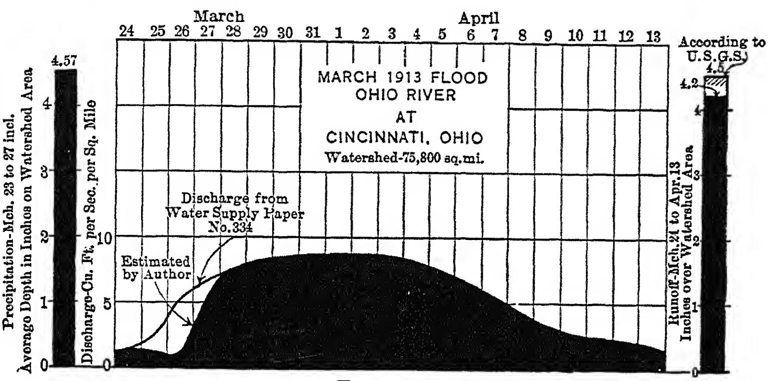


FIG. 218.

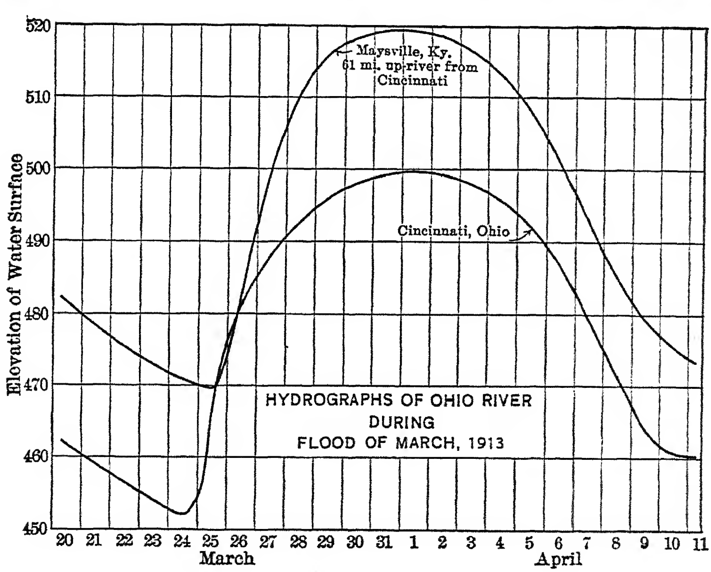


FIG. 219.

The precipitation considered in connection with the Ohio River flood at Cincinnati is that of the entire storm extending from March 23 to 27, 1913, shown in Fig. 220.

MAP SHOWING RAINFALL IN OHIO RIVER BASIN, MARCH 23-27 1913

From U.S.G.S. Water Supply Paper No. 334.

FIG. 220.

Floods Due Primarily to Snowfall

Accumulation of Snow. — The effect of snow in producing flood flows depends, primarily, upon the amount accumulated, and the rate of melting. The watershed area has much less effect on the magnitude and characteristics of floods resulting from snow than on those resulting from rain. A number of

snowstorms passing over a watershed may eventually produce a relatively uniform, deep cover, even though each storm in itself may distribute its moisture quite irregularly.

The possible accumulation of snow on a watershed is dependent both upon the amount of winter precipitation and upon the temperature. In some regions the snowfall is heavy, but the snow melts so soon after falling that little accumulates. In other regions the temperature continues below freezing for months, and the entire winter's precipitation accumulates.

Floods on streams draining watersheds less than 1000 square miles in area, almost invariably result from excessive summer rains. The amount of snow-water likely to be suddenly released through high temperatures and such precipitation as may be expected at the time of break-up in the spring, is usually less than the excessive rain which occasionally falls later in the season.

The rate of rise in temperature, particularly after the snow has become compacted, is an important factor influencing the amount of accumulated precipitation which appears in the streams. A progressive warming up over a watershed decreases the flood heights on streams flowing south, but increases them on streams flowing north. A sudden warming up has the opposite effect. Forests retard the melting of snow, and, in this way, bring the period of break-up later into the spring when the rainfall is heavier. Through this action, particularly if the ground was frozen through the winter, or saturated by fall rains, forests often increase floods, as was illustrated by the flood of the Cedar River, Washington, November 19, 1911, and of the Little Fork River, Minn., April 18, 1916.

Melting of Snow. — Snow melting *slowly* from the sun's heat does not usually produce serious floods, as a large amount of the water is evaporated. On the other hand, warm rains falling on cold snow, alone, will not produce high runoff, either. This fact is well presented by Horton * in the following statement:

* Horton, Robert E., Monthly Weather Review, December, 1905.

> "Thus, to melt one inch of congealed water, or say, five inches compact snow, or ten inches loose, fresh snow with rain at 42 degrees, would require 14.4 inches of rain."

Horton states that the sun's heat will melt snow at the rate of about .05 inch depth of water per 24 hours for each degree the air temperature is above 32° F.

Snow has great capacity for holding water by capillarity against gravity. If the ground under the snow is not frozen, or, if frozen, is not saturated, a surprisingly large amount of percolation will occur when the melting process is gradual. When day and night temperatures both remain above freezing, however, for a few days, so as to reduce the snow to slush and warm rains then set in, the accumulated precipitation quickly finds its way into the streams and produces floods.

Crow Wing River Flood. — Fig. 221, for the Crow Wing River, is a typical hydrograph of a flood due exclusively to melting snow. The physical characteristics of the Crow Wing watershed are given on page 319. While the flood of April, 1916, on this stream is the highest on record, nevertheless, it represents a comparatively small amount of runoff. Most of the melting snow found its way into the ground, or into lakes and ponds.

Little Fork River Flood. — The flood on the Little Fork River, shown in Fig. 222, was due, primarily, to the heavy winter snowfall. It was aggravated, however, by three conditions:

1. The heavy forests retarded the melting of the snow until the heavy April rains set in.
2. The clayey soil was unable to absorb much water, notwithstanding the flat topography, because about $4\frac{1}{2}$ inches of rain had fallen during the previous October and November.
3. The stream flows northward so that the break-up was progressive *down* stream.

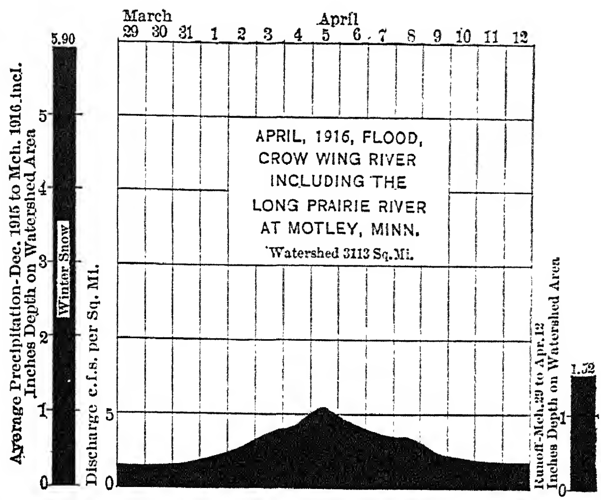


FIG. 221.

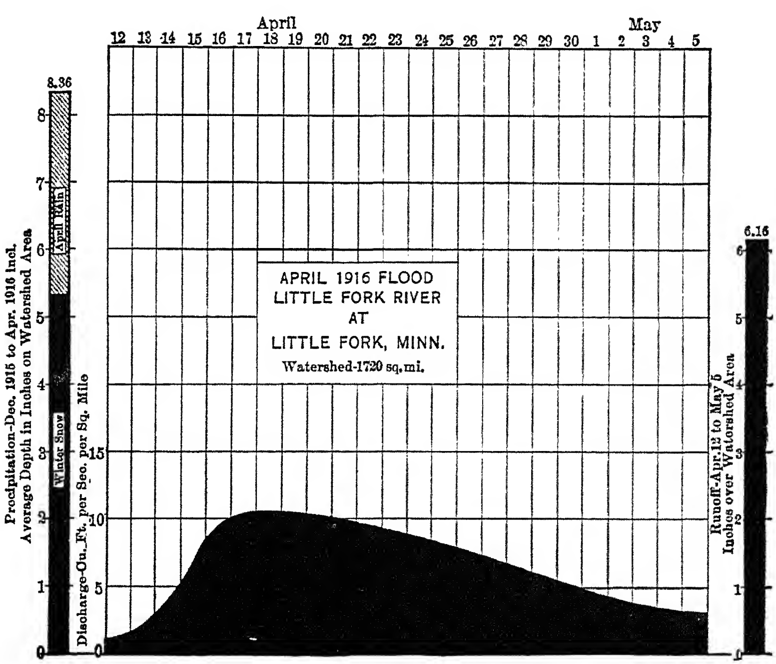


FIG. 222.

After May 5, the Little Fork River fell slowly for about two weeks and then rose again, due to May rainfall, remaining practically at flood stage for about two months.

The inability of heavy forests, when occurring on flat, clayey watersheds, to prevent flood runoff, is clearly shown by the 1916 flood on the Little Fork River. On the other hand, the inability of these same heavy forests to produce a good low-water flow in dry seasons is shown by the fact that the discharge in September, 1910, and during the winter of 1911 to 1912, fell to .05 cubic foot per second per square mile.

Effect of Temperature and Precipitation on Winter and Spring Floods

Figs. 222 to 229 have been prepared to show the combined effect of temperature and precipitation on the flood flow of typical streams.

The Ohio River at Pittsburgh. — The Ohio River watershed above Pittsburgh, Penn., with an area of 19,000 square miles, ranges from rolling to mountainous. The soil cover, on the whole, is thin, and the slopes are steep. Most of the watershed consists of brush-covered, cut-over land. Floods occur mainly in winter because the precipitation is quite uniformly distributed through the year and heavy thaws may be expected at any time. This is clearly shown by the graphs.

Severe floods on this stream are usually the combined result of warm weather and rain. High minimum temperatures appear to be especially effective in bringing the precipitation into the streams. Freezing night temperatures, notwithstanding high day temperatures, have a great retarding influence. This is evident from a study of the peaks on the hydrograph. Combinations of temperature and precipitation that would result in still greater floods very evidently are possible.

The maximum stage on the Ohio River at Pittsburgh was reached on March 15, 1907. As will be noted from Fig. 224, this flood resulted from a light snowfall on March 10, combined

with about $1\frac{3}{4}$ inches of rain and very warm weather a few days later. A more serious flood, however, might easily have occurred. Either the snowfall of February, 1910, or the rainfall of December, 1901, would have greatly increased the flood crest.

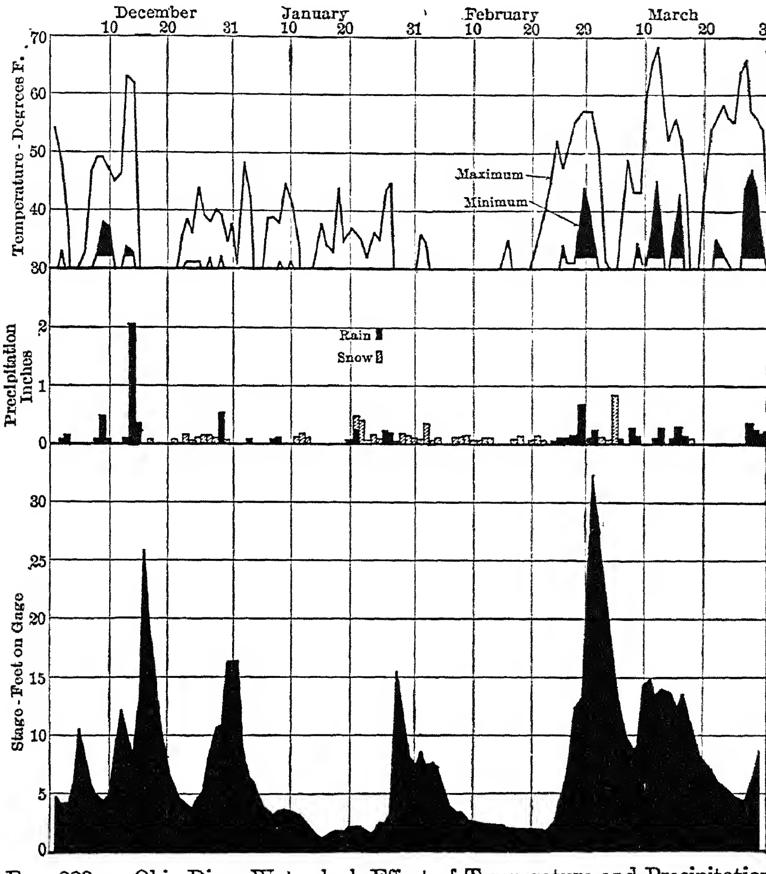


Fig. 223. — Ohio River Watershed, Effect of Temperature and Precipitation on Stage at Pittsburgh, December, 1901–March, 1902.

While the 1907 flood reached the highest recorded stage at Pittsburgh, it was of such short duration and the lower tributaries of the Ohio, except the Green River, Kentucky, delivered so little water, as to result in very ordinary stages in the lower reaches of the stream.

The flood of March 1, 1902, was the second greatest on record, and conditions were favorable for a still greater flood. The winter had been cold and considerable snow had accumulated. The rise in temperature during the last week of February was

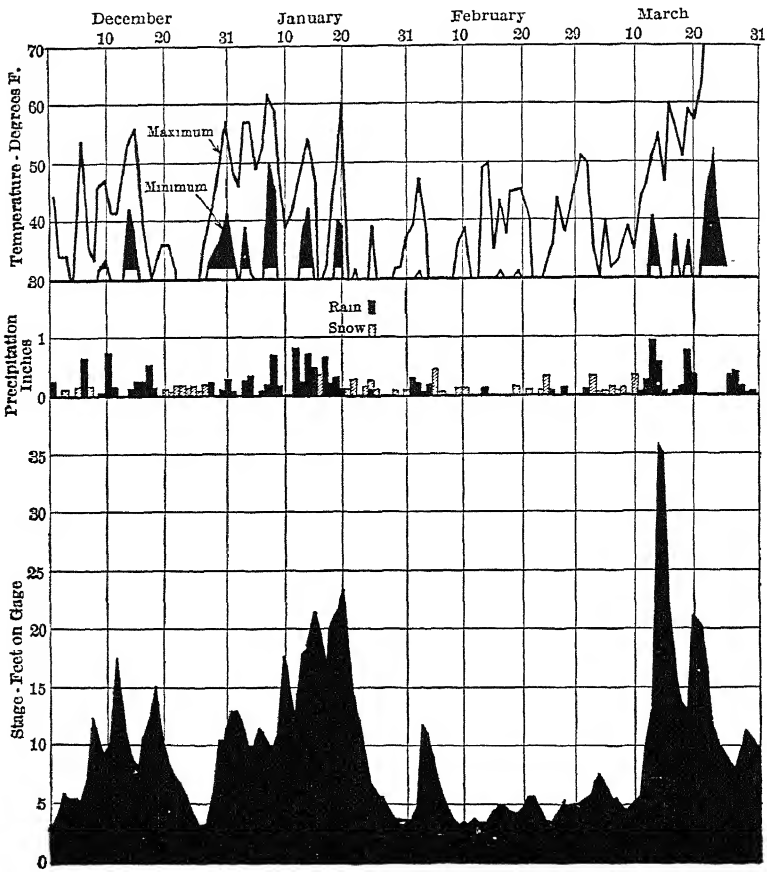


FIG. 224. — Ohio River Watershed, Effect of Temperature and Precipitation on Stage at Pittsburgh, December, 1906–March, 1907.

rapid, the minimum reaching 44 degrees, but very little rain fell. Fig. 223 clearly shows temperature conditions most favorable to a serious flood, and the absence of rain at the critical time.

A situation almost equally favorable to a record-breaking flood existed in the spring of 1910. If the minimum temperature

of 45 degrees on February 27 had been accompanied by even an inch and a half of rain, a great flood would have followed. The large amount of water that ran off, notwithstanding the small March precipitation, is well shown in Fig. 225.

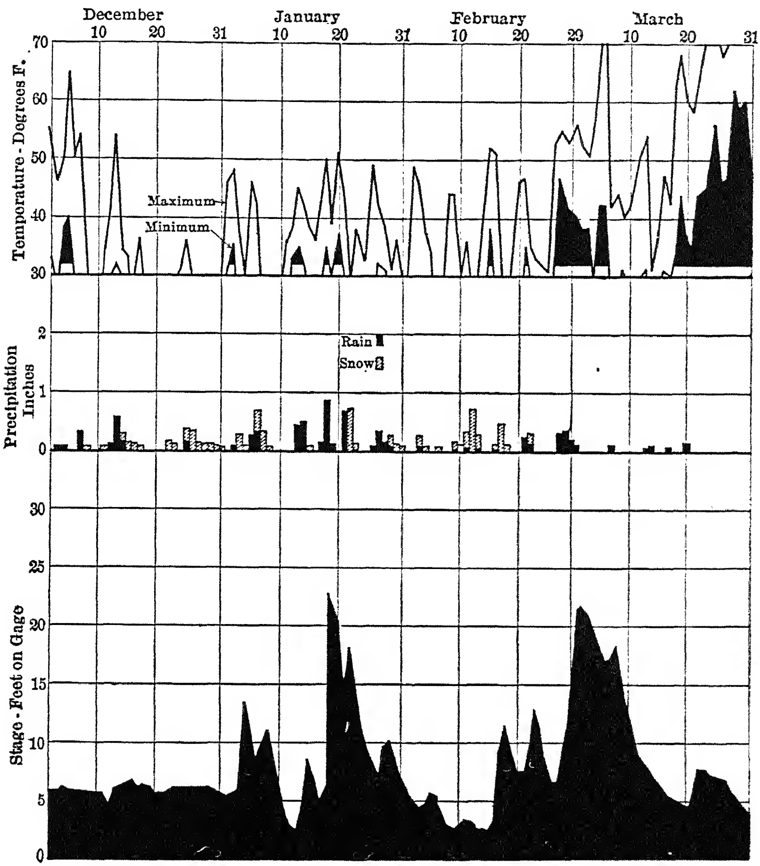


Fig. 225. — Ohio River Watershed, Effect of Temperature and Precipitation on Stage at Pittsburgh, December, 1909–March, 1910.

The Upper Mississippi River at St. Paul, Minn. — The Mississippi River at St. Paul, Minn., drains an area of 35,700 square miles, consisting of the watershed of the Mississippi proper and that of the Minnesota River. The watershed consists of relatively flat and gently rolling land, considerable

portions of which are distinctly sandy. At least half of the land is under cultivation. Only a small portion of the watershed is heavily forested. Portions of the watershed drained by the Minnesota River are relatively flat, have a heavy clay soil and yield little runoff under ordinary conditions.

The greatest flood on record is that of 1881, when a stage of 19.1 feet on the gage was reached, corresponding to a discharge variously estimated at from 95,000 to 120,000 second-feet. While the meteorological data for 1880 to 1881 are very meager, the flood appears to have been the result of rather general heavy winter and early spring precipitation.

The second greatest flood occurred in March and April, 1897. A stage of 18.0 feet, corresponding to a discharge of 85,500 c.f.s., was reached on April 6. This flood also resulted from a heavy winter snowfall. November, 1896, was a cold month, and the precipitation over the State averaged 2.69 inches. This was greatly in excess of the normal. In December the precipitation was about normal, but in January, February and March, 1897, about 5 inches of snow fell, making a total winter precipitation of a little over 8 inches. The early part of March continued severely cold. Up to March 27, the day temperatures rose only slightly above freezing. Then a warm spell set in. From March 28 to 31, the day temperatures reached a maximum of from 50 to 55 degrees, and the night temperatures ranged from freezing to 6 degrees above. There was no precipitation during the last week of March, and the April precipitation was only half the normal.

The temperature and precipitation on the watershed during both the spring of 1897 and 1916 are shown in Figs. 226 and 227.

In 1916 conditions were favorable for a greater flood than in 1897, until the weather suddenly turned colder again the last days in March, making the break-up much more gradual than in 1897. Renewed warm weather and rains resulted in a secondary rise after April 20, 1916.

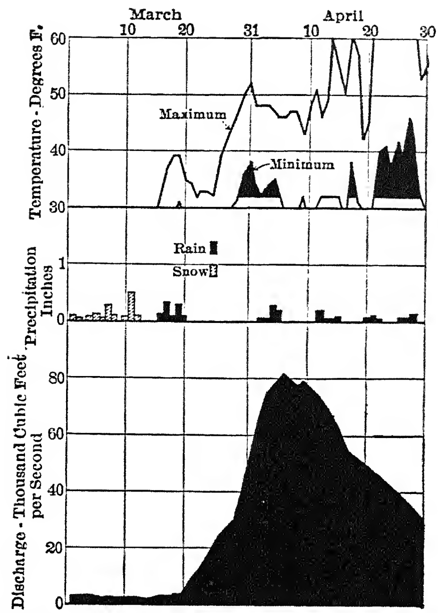


FIG. 226. — Mississippi River Watershed, Effect of Temperature and Precipitation on Discharge at St. Paul, 1897.

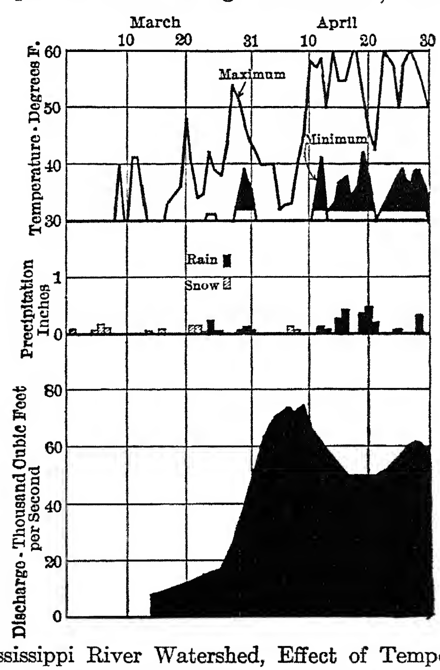


FIG. 227. — Mississippi River Watershed, Effect of Temperature and Precipitation on Discharge at St. Paul, 1916.

The Red River of the North at Grand Forks. — The Red River of the North drains an area of 35,895 square miles above the international boundary, most of which is prairie land with flat slopes and heavy soil.* The fall from Lake Traverse to the City of Winnipeg, a distance of over 500 miles by river, and little more than half that distance in a direct line, is only about 225 feet. From that point to the outlet in Lake Winnipeg the fall is considerably greater.

Information regarding early floods is meager. The first great flood of which there is any record is that of 1826, when the river is reported to have risen 66 feet above low water. Snow fell in Pembina on October 15, 1825, and remained on the ground throughout the succeeding cold winter, resulting in a spring flood. The next great flood occurred in 1852 when the gage reached 67 feet above low water.

The greatest flood regarding which there is reliable information occurred in 1897. It began in the upper reaches on April 1, and crested at Moorhead, April 5, and at the international boundary about three weeks later. A stage of 50.2 was reached at Grand Forks on April 10. There was no rain during the last week of March and the April precipitation was only half the normal. The flood resulted entirely from the melting of a heavy winter snowfall. During this flood, a strip of country about 30 miles in width and 150 miles in length, was inundated, and about 50,000 people were rendered homeless.

The temperature and precipitation on the watershed during both the 1897 and the 1916 floods are shown in Figs. 228 and 229.

The cold weather during the first week of April, 1916, affected the runoff from the Red River watershed, at Grand Forks, in a similar manner to that from the Mississippi. If the rains between April 15 and 20 had come ten days earlier, or the weather had even continued warm, record-breaking floods would have occurred on both the Red and the Mississippi Rivers in 1916.

Mass Curves of Temperatures Above Freezing. — Figs. 230 to 234 show a summation of temperatures above freezing,

* See Bulletin No. 1017, U. S. Dep't of Agr., 1922, and Quarterly Journal Univ. of N. D., April, 1911.

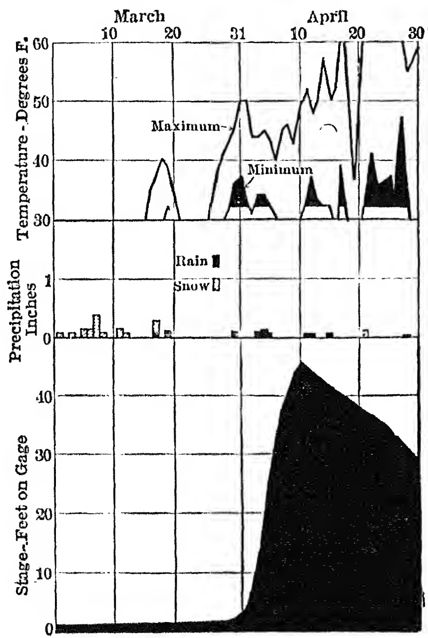


Fig. 228. — Red River Watershed, Effect of Temperature and Precipitation on Stage at Grand Forks, 1897.

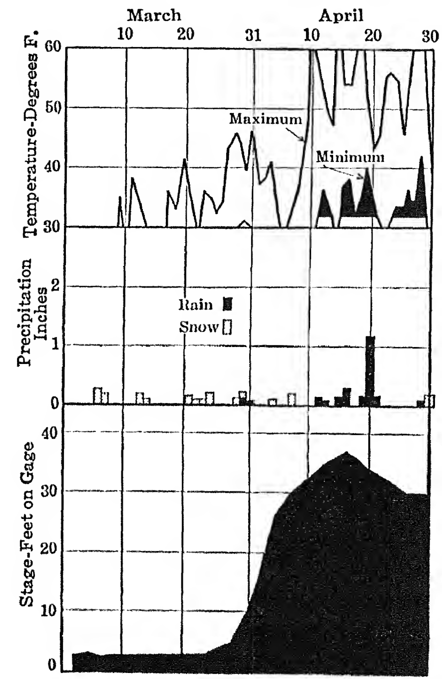


Fig. 229. — Red River Watershed, Effect of Temperature and Precipitation on Stage at Grand Forks, 1916.

with a view to illustrating the effect of spring temperatures on the flow of streams, in another manner. The break-up was much more nearly simultaneous over the entire state of Minnesota in 1897 than in 1916. While ordinarily the Minnesota River breaks up before the Mississippi, bringing its flood water to the mouth, at St. Paul, before that from the northern part of the State arrives, in 1897 both streams crested at almost the same time. It appears that any one of three conditions would have produced greater floods in the Mississippi River at St. Paul, in 1916, than actually occurred:

1. More nearly uniform temperature conditions, as in 1897.
2. Continued warm weather for five days longer.
3. Moderately heavy rains ten days earlier.

Figs. 230 to 234 give an interesting indication of the amount of warm weather required, in spring, to bring northern streams to flood stage. In 1897, the Mississippi River crested on April 3, when the total number of degree-days of maximum daily temperature above 32° F. aggregated 170. In 1916 the crest occurred on April 6 at 175 degree-days.

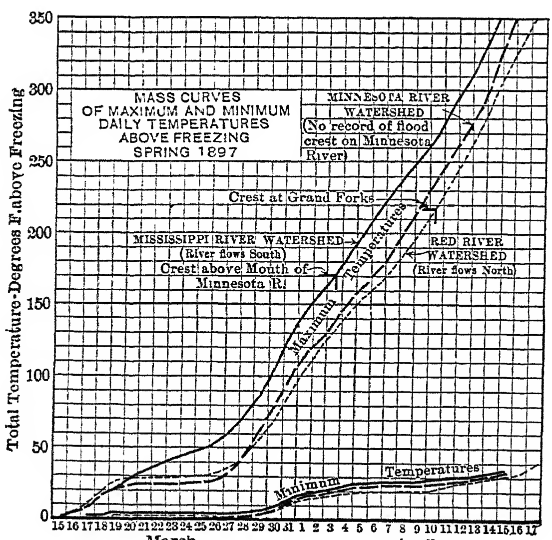


Fig. 230.

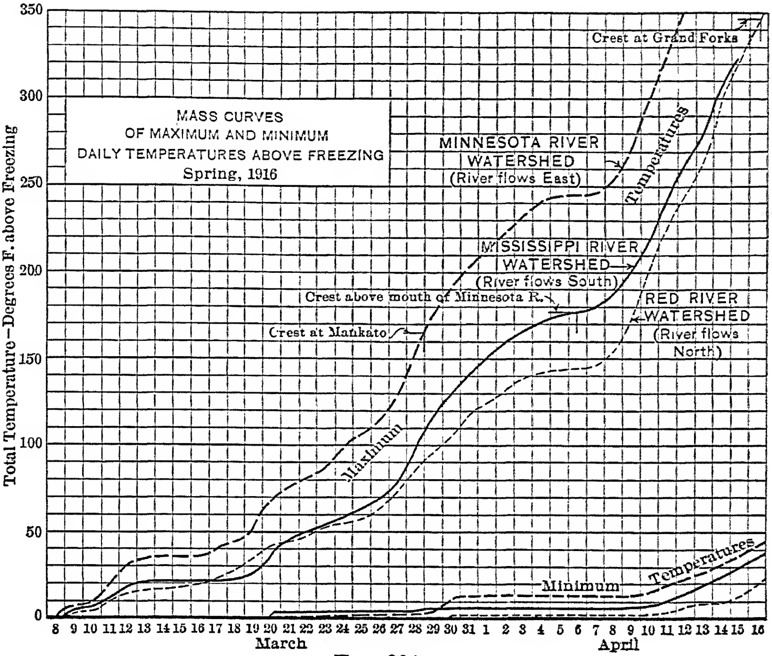


FIG. 231a.

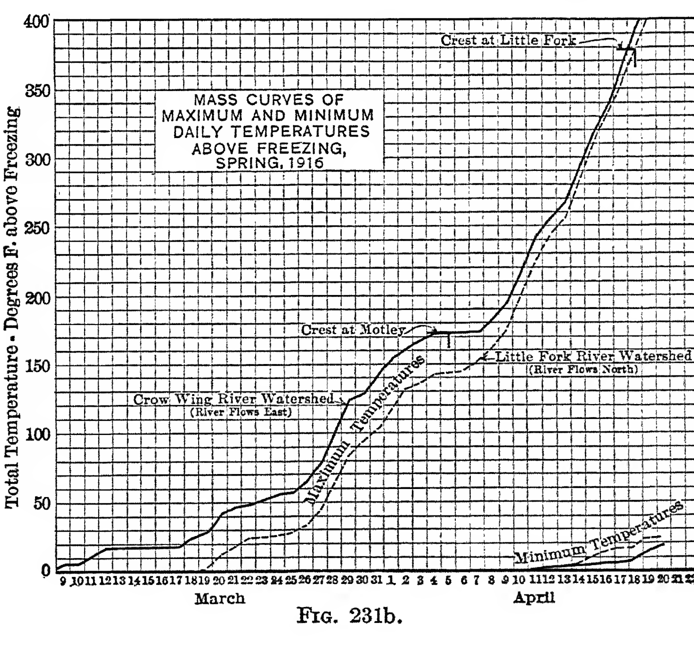


FIG. 231b.

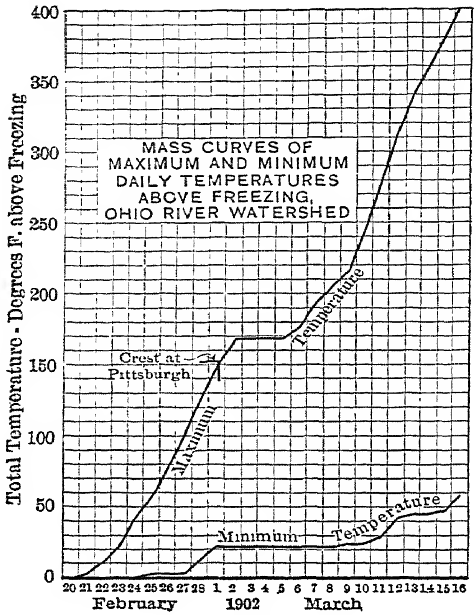


Fig. 232.

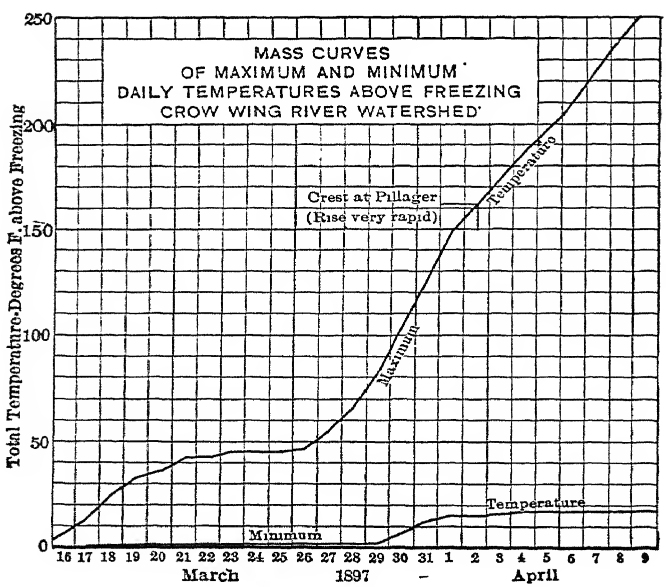


Fig. 233.

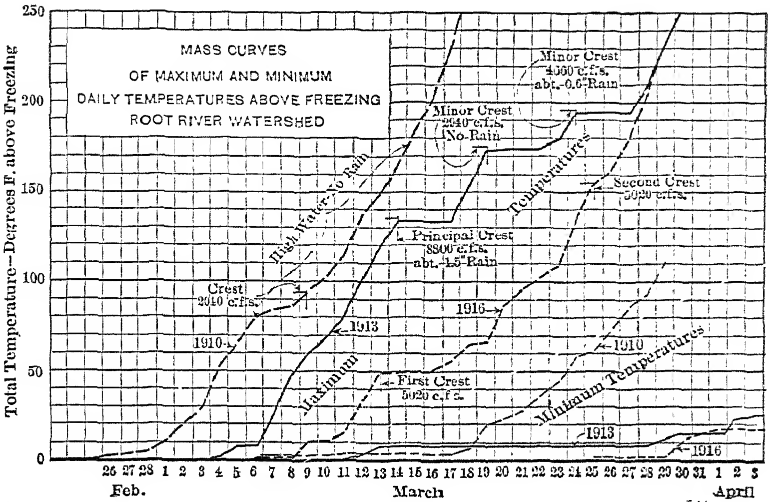


Fig. 234.

The Minnesota River crested at 165 in 1916. No record of crest is available for 1897. In 1902 the Ohio River crested, at Pittsburgh, at 150 degree-days. The Crow Wing crested at 165 in 1897, and at 172 in 1916. The Root River reached its highest at 95 in 1910 although there really was no crest at all. High water extended over the entire period from 80 to 175 degree-days. In 1913, the Root River crested at 135. Cold weather resulted in a rapid drop in stage with a second crest at 175. Then, another spell of cold weather set in and a third crest occurred at 195. In 1916 the first crest on the Root River occurred at 50 and a second and equal crest at 155. Neither crest was caused by rain.

Both the Red River and the Little Fork streams, flowing north, crested much later, in 1916, than the streams flowing south. The Little Fork crested at 375 and the Red, a much larger stream, at 345. The forests on the Little Fork River watershed unquestionably retarded the melting of snow and contributed materially to the late crest. The Red River watershed is from one-half to two-thirds prairie land.

In 1897 the temperature rise was rapid, continuous and

almost simultaneous over the Northwest and the Red River of the North crested at 215.

It is also interesting to note that the crest of the Ohio River flood at Pittsburgh on March 1, 1902, occurred before the weather turned colder again, so that the full effect of the melting of the snow, combined with the rain, was felt. In case of the Root River, Minnesota, floods of March, 1913 and 1916, on the other hand, the crest was considerably lower than it would have been if warm weather had prevailed a few days longer.

Fall Floods

Many streams draining watersheds on which the summer and fall precipitation is heavy, are subject to fall floods. The Passaic River, N. J., flood of October 8, 1903, is a typical fall flood, and the greatest recorded for the stream. The Passaic River drains a steeply sloping, hilly fan-shaped area of 772 square miles above Patterson, N. J. The flood was caused by a 30-hour rainstorm which averaged a precipitation of between 10 and 12 inches.

Many streams in the upper Mississippi Valley are subject to late summer and fall floods. A typical example is the October, 1911, flood on the Black River, Wisconsin.

The occurrence of summer and fall floods on streams greatly complicates the problem of the storage of water for combined power, navigation, and flood prevention purposes. This subject will be discussed in a later chapter.

Flood Flow Formulas

A large number of formulas have been prepared for the purpose of computing the probable flood flow from watersheds of various sizes. One group of formulas, including such well-known ones as McMath's, Hawksley's, Bürkli-Ziegler's, Adams', Hering and Gregory's and Parmley's, are intended, primarily, for use in sewer design and are applicable, particularly, to small areas

of less than one or two thousand acres. Other formulas, such as Kuichling's, Murphy's, Metcalf & Eddy's, and Fuller's, are applicable to the larger drainage areas. For a detailed discussion of these and other formulas, the reader is referred to books on sewerage. A discussion of some of the principles involved is, however, within the scope of this treatise.

Weight Given to Various Factors by Different Formulas. — Most of the formulas of that group applicable to sewer design assume the runoff in cubic feet per second to vary as the rate of rainfall in inches per hour, approximately as the .25 power of the slope of the ground, and approximately as the .8 power of the drainage area. The proportion of the rainfall reaching the sewers, dependent upon the character of the watershed, is usually expressed in a coefficient. Kuichling * concluded that, theoretically, the fourth root of the factor "$\frac{1}{\text{area}}$" was the proper one to use.

Of the group of formulas applicable to estimates of flood flows from larger drainage areas, Kuichling's, Murphy's, and Metcalf & Eddy's assume only one variable, namely, the area of the watershed. The magnitude of floods, with respect to the interval of successive occurrences, is expressed in the coefficient used. Floods are grouped as "frequent," "occasional," "rare," "maximum," etc. The relation of watershed area to flood flow in second-feet per square mile, according to these formulas, is shown in Fig. 235.

Fuller Formulas. — Fuller† introduces another variable into his formula, namely, the interval of time within which floods of a given magnitude are likely to recur.

Watershed characteristics are taken care of, as far as possible, by a coefficient. Fuller's relation between the size of drainage basin and ratio of maximum flood to average 24-hour flood is shown in Table 38.

* Kuichling, Emil, Trans. Assoc. C. E., Cornell University, 1893.

† Fuller, Weston E., Trans. Am. Soc. C. E., Vol. LXXVII, p. 564, 1914.

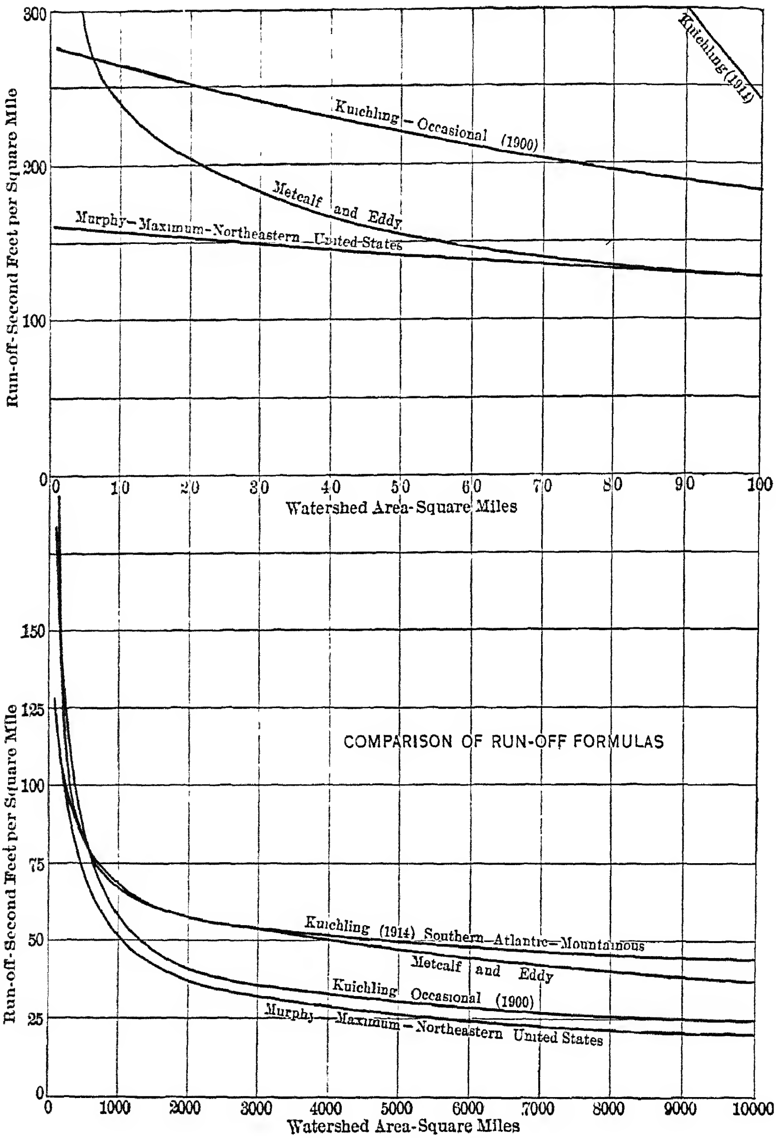

Run-off-Second Feet per Square Mile
Kuichling (1914)
Kuichling – Occasional (1900)
Metcalf and Eddy
Murphy – Maximum – Northeastern United States
300
200
100
0
0 10 20 30 40 50 60 70 80 90 100
Watershed Area-Square Miles
COMPARISON OF RUN-OFF FORMULAS
Kuichling (1914) Southern-Atlantic-Mountainous
Metcalf and Eddy
Kuichling Occasional (1900)
Murphy – Maximum – Northeastern United States
150
125
100
75
50
25
0
0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000
Watershed Area-Square Miles

FIG. 235.

TABLE 38. — RELATION BETWEEN MAXIMUM FLOOD AND AVERAGE 24-HOUR FLOOD (Fuller)

$$Q\ (\text{max.}) = Q\ (1 + 2\,A^{-0.3})$$

Catchment area, in square miles (1)	Ratio of maximum flood to average 24-hour flood (2)	Catchment area, in square miles (1)	Ratio of maximum flood to average 24-hour flood (2)
0.1	5.0	500	1.31
1.0	3.0	1,000	1.25
5.0	2.23	5,000	1.15
10.0	2.0	10,000	1.12
50.0	1.62	50,000	1.08
100.0	1.5	100,000	1.06

Fuller's relation between the flood to be expected in a given period of years and the average yearly flood is shown in Table 39.

TABLE 39. — RELATION BETWEEN FLOOD TO BE EXPECTED IN A SERIES OF YEARS AND THE AVERAGE YEARLY FLOOD (Fuller)

$$Q = Q\ (\text{ave.})\ (1 + 0.8 \log T)$$

Time, in years (1)	Ratio of largest flood to average yearly flood (2)	Time, in years (1)	Ratio of largest flood to average yearly flood (2)
1	1.00	50	2.36
5	1.56	100	2.60
10	1.80	500	3.16
25	2.12	1000	3.40

This table is based upon the conclusion that the greatest flood which is likely to occur in the period of T years will exceed the average annual flood by .8 log T times the average annual flood.

The variation of the ratio of maximum flood flow, in cubic feet per second, to the average 24-hour flow, in cubic feet per second, with size of drainage area, represents a physical reality, although the ratio is also largely dependent on the characteristics of the watershed. The statement of the magnitude of flood, measured by the average annual flood on the given watershed, to be expected in a certain number of years, represents

merely a "probability" based on average observed occurrences. The maximum flood of a century may occur within five years' records of stream flow, yet, according to the law of probabilities as applied by Fuller, the flood to be expected in a period of one hundred years would still exceed this observed maximum of a century by nearly 70 per cent. When meteorological and hydrological data are entirely wanting, so that the cause of floods on the given stream cannot be studied, the use of such formulas as Fuller's may be justifiable, in that they serve as a rough guide.

The lack of reliance to be placed on a formula giving the probable frequency of floods is well illustrated by the 1913 floods in the Ohio Valley and in northeastern United States.

The Hudson River at Mechanicsville, N. Y., drains an area of 5400 square miles. Records extend back about a hundred years, although accurate data are not available for the early years. According to Horton * the average of the highest day's discharge for each year of the 26 years preceding 1914 was 41,875 second-feet. The greatest flood previous to 1913 occurred in the spring of 1869, when the peak reached 67,000 second-feet. The crest of the 1913 flood reached 113,500 second-feet. This flood was preceded by warm rains that had taken most of the frost out, saturated the ground, and exhausted substantially all natural lake and swamp storage. The streams were at a bankful stage but there was no accumulation of snow on the ground except in a small portion of the Adirondack forests. An average of $4\frac{1}{2}$ to 5 inches of rain fell on the upper Hudson River watershed on March 25, 26, and 27, on practically saturated soil.

Flood Frequency. — The frequency of flood stages on the Ohio River at Pittsburgh and at Cincinnati is shown in Figs. 236 and 237. By extending these curves an estimate can be made of the probable frequency of still greater floods which are likely to occur. Not much weight can be placed on such

* Horton, Robert E., Engineering Record, 1913, Vol. 66, p. 399.

estimates, however. Up to a frequency of one flood in 25 years, the curves should be quite reliable.

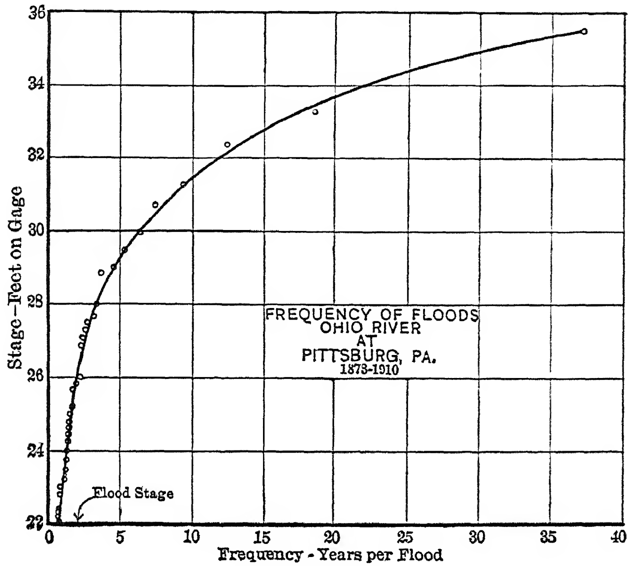


FIG. 236.

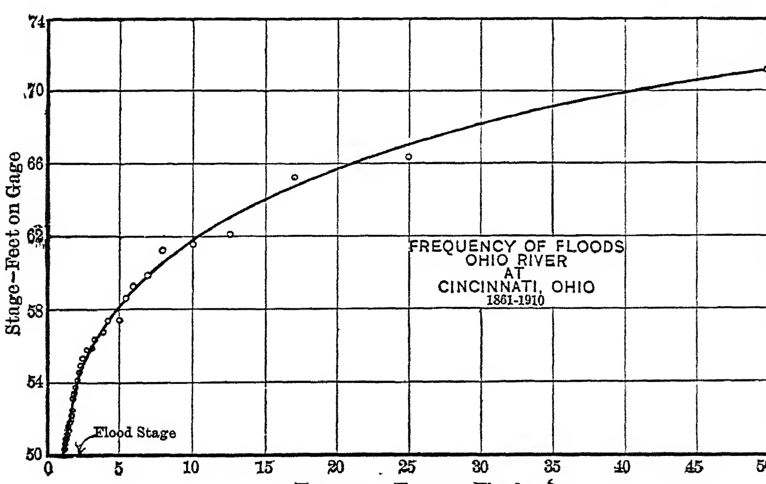


FIG. 237.

Suggested Definition of "Normal." — Fig. 238 shows the frequency of river stages between extreme low water and extreme high water, at Cincinnati, for 50 years. In this connection it is interesting to consider what constitutes the "normal" stage of a stream or the "normal" annual, monthly, or daily precipitation at a given station. The definition of "normal" applicable

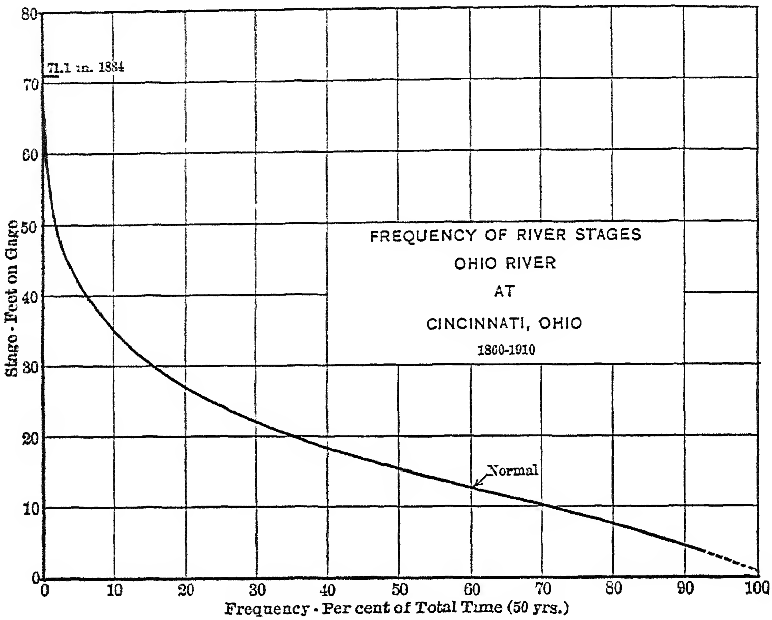


FIG. 238.

to such phenomena would seem to be that given by Webster, as follows:

> "The ordinary or usual condition, degree, quantity, or the like."

According to this definition, the term "normal" river stage would mean that stage which prevails the greatest percentage of the time. Such a stage is represented by the point of inflection or change of curvature on the frequency curve, and represents a very much lower stage than the mean, or average.

Minnesota Flood Flow Formulas. — Since the first edition of this book was published the author, while acting as Consulting Engineer to the Department of Drainage and Waters, State of Minnesota, with the aid of Carl M. Halseth, Asst. Engr., developed the following flood flow formula, particularly for Minnesota conditions:*

$$Q = 100\, A^{.6}.$$

Where "Q" = the maximum flood flow, in cubic feet per second, to be expected, on an average, once in twenty-five years, from ordinary, gently rolling, drainage basins having an area "A" in square miles.

For other frequencies than once in twenty-five years multiply "Q" by the proper frequency coefficient.

FREQUENCY COEFFICIENTS "C_1"

For a flood of magnitude to be expected	Coefficient
Once in 10 years.........	.85
Once in 25 years.........	1.00
Once in 100 years.........	1.40

For drainage basins of different slope, character of soil, and topography, multiply "Q" by the proper runoff coefficient.

* Drainage Areas of Minnesota Streams and Method of Estimating Probable Flood Flows — Dep't of Drainage and Waters, State of Minnesota, E. V. Willard, Commissioner, October, 1922.

RUNOFF COEFFICIENTS "C_2"

Character of Drainage Basin	Coefficients		
	Sandy Soil	Loam	Clayey Soil
1. Very flat agricultural or timber land with some marshes and swamps	.35	.40	.50
2. Relatively flat agricultural or timber land with some marshes and ponds..	.45	.50	.60
3. Gently rolling agricultural or timber land full of lakes, ponds and marshes connected by poorly defined water courses.......	.50	60	75
4. Relatively flat agricultural or timber land of fairly uniform slope, without lakes and ponds ...	.60	.70	.85
5. Slightly undulating agricultural or timber land without lakes or ponds; or distinctly rolling to hilly agricultural or timber land, with lakes and ponds	.70	.80	1.00
6. Gently rolling agricultural or timber land without lakes and ponds.	.85	1.00	1.25
7. Distinctly rolling to hilly agricultural or timber land without lakes and ponds; or hilly agricultural or timber lands with steep slopes and lakes, ponds and marshes in valleys	1.10	1 50	2.00
8. Hilly agricultural or timber land with steep slopes barely admitting of cultivation; without lakes, ponds or marshes......................	2.25	3 00	4.00
9. Very hilly timber or brush-covered land, slopes too steep for cultivation; ravines and gullies with occasional small ponds or marshes	3.50	4.50	6.00
10. Very hilly timber or brush-covered land with some rock outcropping; ravines and gullies, and occasional small ponds or marshes....	5.00	6.00	8.00
11. Very hilly to rugged country with much rock outcropping; scattered timber; occasional small ponds and marshes................ . . .	9.00	10.00	12.00
12. Rugged to precipitous rocky country with practically no soil cover; small timber and brush; ravines and gullies; no lakes, ponds or marshes to retard runoff	.....	15.00	......

Note. — The available information on the subject does not indicate that forests have any material effect upon the extreme flood flow. They have a tendency to reduce the ordinary flood flow somewhat. In northern Minnesota forests have aggravated spring floods by retarding the melting of snow until warm April rains set in.

In determining the proper coefficient to use for a given drainage basin of diverse characteristics, subdivide the basin into approximately similar areas, select the proper coefficient for each subdivision, and compute the average coefficient applicable to the entire area.

In general, it may be stated that lakes, ponds and marshes have a most pronounced retarding effect upon the runoff, resulting in low coefficients. A region may be hilly — even rocky — but between the hills and rock outcrops there may be lakes, ponds, marshes, bogs or muskegs, which greatly retard the flow of water to the main stream, even though the rainfall rapidly runs off from the hills into the valleys where the lakes, ponds and marshes lie. Drainage basins having a relatively uniform slope in one direction, particularly if gullied, would require the use of large coefficients.

For convenience in making computations a curve of values for $A^{.6}$ may be plotted from the following table.

VALUES OF $A^{.6}$ FOR USE IN THE FORMULA $Q = 100\ A^{.6}$

A = Area in Square Miles	$A^{.6}$
100,000	1000
70,000	807
40,000	577
30,000	486
20,000	381
10,000	251
7,000	203
4,000	145
3,000	122
2,000	96
1,000	63
700	51
400	36
300	31
200	24
100	16
70	13
40	9.1
30	7.7
20	6.0
10	4.0
7	3.2
4	2.3
3	1.9
2	1.5
1	1.00
0.7	0.81
0.4	0.58
0.3	0.48
0.2	0.38
0.1	0.25
0.05	0.17
0.01	0.06

The formula developed for Minnesota conditions seems to apply fairly well to other areas as the following tables show. The observed data given in these tables are taken from a paper by Jarvis in Trans. Am. Soc. C. E., 1926.

MISSISSIPPI RIVER FLOODS

Illustrating Effect of Size and Character of Drainage Basin

Gaging station	Drainage area, sq. mi.	Observed discharge, c f s.	Computed discharge $Q = 100\ C_1C_2A^{.6}$				Remarks
			$A^{.6}$	C_1	C_2	Q	
Above Sandy	4,510	9,450	155	1.0	6	9,300	Reservoir controlled
Sauk Rapids	12,400	50,800	286	1.3	1.3	48,500	
Anoka . . .	17,100	49,100	347	1.3	1.4	63,200	
St. Paul, Minn	36,055	120,000	542	1.3	1.8	127,000	Below Minn. Riv.
Clayton, Iowa.	79,040	210,000	868	1.3	1.9	214,000	Below Wis River
Grafton, Ill	171,570	360,000	1382	1.3	2.0	359,000	
St. Louis, Mo	702,380	900,000	3221	1.3	2.2	920,000	Below Mo. River
Cairo, Ill. .	902,900	2,000,000	3744	1.3	4.0	1,950,000	Below Ohio River
Helena, Ark.	1,000,000	2,040,000	3981	1.3	3.8	1,970,000	
Carrollton, La.	1,400,000	1,500,000	4872	1.3	3.3	2,090,000	

The flood at Cairo, Ill., was produced primarily by the Ohio River. The character of this drainage basin and the rainfall on it as compared to Minnesota conditions, warrant the use of $C_2 = 4.0$. The dominating influence of Ohio River floods on the flow in the lower Mississippi is expressed in the use of a much larger coefficient on the lower than on the upper river.

OHIO RIVER FLOODS

Illustrating Effect of Size and Character of Drainage Basin

Gaging station	Drainage area, sq. mi.	Observed discharge, c.f.s.	Computed discharge $Q = 100\ C_1C_2A^{.6}$			
			$A^{.6}$	C_1	C_2	Q
Monongahela River, Lock No. 4, Pa. . .	5,430	206,000	174	1.3	9	204,000
Allegheny River, Kittanning, Pa.	9,010	270,000	235	1.3	9	275,000
Ohio at Pittsburg, Pa. . .	19,100	440,000	370	1.3	9	433,000
Ohio at Wheeling, W. Va.	23,800	510,000	423	1.3	9	496,000
Ohio at Louisville, Ky. . .	90,600	770,000	943	1.3	7	860,000
Ohio at Cairo, Ill. .	233,000	1,400,000	1661	1.3	6	1,300,000

The fact that the computed discharge agrees very well with observed values even though the same coefficient is used for areas varying from 5430 to 23,800 square miles, because these areas are quite similar in character, indicates that the flood flow varies substantially as the six tenths power of the drainage area in square miles.

MAXIMUM OBSERVED FLOODS IN VARIOUS DRAINAGE BASINS

Compiled from paper "Flood Flow Characteristics" by C. S. Jarvis in Trans. Am. Soc. C. E. 1926

	River and locality	Drainage area, sq mi.	Discharge cu sec ft per sq. mi	Date
1	Docker's Hollow, North Braddock, Pa.	0.6	4000	June 1917
2	Skyrocket Creek, Ouray, Colo.	1.0	2000	July 1923
3	Mad Creek, Leroy, N. Y.	1.5	2300	May 1916
4	Missouri Canyon, near Masonville, Colo.	2.4	1820	June 1923
5	Honey Creek, West Fork, New Carlisle, Ohio	3.5	1000	July 1918
6	Hull's Gulch, Boise, Idaho	5.0	1000	July 1913
7	Hogan's Gulch, Eden, Colo.	6.1	1580	Aug 1904
8	Honey Creek, East Fork, New Carlisle, Ohio	6.7	2210	July 1918
9	Cameron Arroyo, near Pueblo, Colo.	7.3	1900	June 1921
10	Sawpit Canyon, Los Angeles, Calif.	7.4	550	1889
11	Arroyo, Indiole, N. Mex.	8.9	1105	July 1915
12	Honey Creek, East Fork, New Carlisle, Ohio	11.8	1285	July 1918
13	Mill Creek, Erie, Pa.	12.9	1000	Aug. 1915
14	Panther Creek, Iowa	14.0	520	June 1905
15	Rocky Creek, near Ellisville, Miss.	15.0	1110	May 1882
16	Le Noir Coulee, Malta, Mont.	16.0	538	June 1906
17	Alazon Creek, San Antonio, Tex.	17.1	1515	Sept. 1921
18	Willow Creek, near Heppner, Ore.	20.0	1800	June 1903
19	Cane Creek, Bakersville, N. C.	22.0	1341	May 1901
20	Dry Run, Decorah, Iowa	22.3	720	Mar. 1915
21	Arroyo Seco, near Pasadena, Calif.	30.5	374	Feb. 1914
22	San Antonio, San Antonio, Tex.	34.3	691	Sept. 1921
23	Lake Roland, Maryland	39.0	230	1868
24	Elkhorn Creek, Keystone, W. Va.	44.0	1363	June 1901
*25	Darby Creek, near Philadelphia, Pa.	48.0	580	Aug. 1843
26	Conemaugh, causing Johnstown flood, Pa.	48.6	206	May 1889
27	Lost Creek, above Dayton, Ohio	52.0	571	Mar. 1913
28	Santa Ysabel Creek, Mesa Grande, Calif.	53.4	395	Jan. 1916
*29	Chester Creek, near Philadelphia, Pa.	62.0	1000	Aug. 1843
30	San Antonio Creek, Tex.	85.0	499	Sept. 1921
31	Otay, Lower Otay Dam, Calif.	98.6	379	Jan. 1916
32	Tohickon Creek, Mt. Pleasant, Pa.	102	138	May 1894
33	Nashua River, Massachusetts	109	104	1848
34	Santa Ysabel Creek, near Ramona, Calif.	110	258	Jan. 1916
35	Ramapo, Mahwah, N. J.	118	106	Oct. 1903
36	Walnut Canyon, near Flagstaff, Ariz.	128	82	Sept. 1923
37	Payette, North Fork, Lardo, Idaho	131	32	June 1909
†38	Devil's Creek, near Viele, Iowa	143	600	June 1905
39	Salado Creek, Salado, Tex.	148	966	Sept. 1921
40	Perkiomen Creek, Frederick, Pa.	152	116	May 1894

* See Table 13, page 190 which shows record rainfall of 5.5 inches in 40 minutes at Newton, Pa. and 10.0 inches at Brandywine, Pa. in the Philadelphia region on August 5, 1843. (Author.)

† See page 134 for a map of the rainstorm causing this flood. An average of 8.72 inches of rain fell in something less than 24 hours on this drainage basin in June, 1905. (Author.)

MAXIMUM OBSERVED FLOODS IN VARIOUS DRAINAGE BASINS. — (*Continued*)

Compiled from paper "Flood Flow Characteristics" by C. S. Jarvis in Trans. Am. Soc. C. E. 1926

	River and locality	Drainage area, sq. mi.	Discharge cu sec ft per sq. mi.	Date
41	Mora River, below Mora, N Mex.	159	140	Sept. 1904
42	Baker River, near Anderson Creek, Wash.	184	200	Dec. 1917
43	Seekonk, Providence, R. I.	190	57	1867
44	Catskill Creek, South Cairo, N. Y.	210	100	Spring 1901
45	Schoharie Creek, Prattsville, N. Y.	236	123	Sept. 1924
46	Bear River, Van Trent, Calif.	262	336	Feb. 1907
47	Twin Creek, Germantown, Ohio	270	244	Mar. 1913
48	Yamhill River, Sheridan, Ore.	290	62	.
49	San Dieguito, Bernardo, Calif.	299	241	Jan. 1916
50	Gunpowder River, Maryland	302	83	.. 1889
51	Deerfield River, Charlemont, Mass.	332	126	July 1915
52	Great River, Westfield, Mass.	350	151	1878
53	West Canada Creek, Hinckley, N Y.	372	105	Apr. 1869
54	San Diego River, Santee, Calif.	375	187	Jan. 1916
55	Pompton, Two Bridges, N. J.	380	62	1903
56	Pacolet River, Spartansburg, S. C.	400	89	June 1903
57	Esopus Creek, at Saugerties, N. Y	417	132	Dec. 1878
58	San Gabriel River, Georgetown, Tex.	431	371	Sept. 1921
59	San Diego River, San Diego, Calif.	434	173	Jan. 1916
60	Whetstone, Big Stone City, S. Dak.	441	3	. ...
	" " " " "	441	18 (Meyer)	June 1919
61	Whiteface, below Meadowlands, Minn.	446	13	. 1916
62	Stillwater, Sugar Grove, Ohio	448	115	Mar. 1913
63	Union River, near Junction, Me.	452	50	Apr. 1923
64	St. Charles River, Pueblo, Colo	482	149	June 1921
65	Yakima River, Cle Elum, Wash.	500	51 2	Nov. 1906
66	Clear Fork of Trinity, Fort Worth, Tex	522	142	Apr. 1922
67	Santa Catarina River, Monterey, Mexico	544	432±	Aug. 1909
68	Occoquan Creek, Occoquan, Va.	546	38 3	1915
69	San Luis Rey, Oceanside, Calif.	565	169	Jan. 1916
70	Sun, North Fork, Augusta, Mont.	600	54	June 1916
71	Bad River, near Odanah, Wis.	607	20	Apr. 1916
72	Pennigewasset, Plymouth, N. H.	615	49 8	July 1907
73	Des Plaines, Riverside, Ill.	630	20 8	. 1889
74	Naches River, Nile, Wash.	640	34	Nov. 1906
75	Mad River, Osborn, Ohio	649	117	Mar. 1913
76	Milwaukee River, Milwaukee, Wis.	661	18 3	Mar. 1918
77	Black River, Neillsville, Wis.	675	34 2	. . . .
78	Little Tennessee River, Jackson, N. C.	675	85 3	Dec. 1901
79	Willamette, Coast Fork, Goshen, Ore.	690	45.4	. . . . . .
80	Broad River, near Carlton, Ga.	762	62	Aug. 1908
81	Passaic River, Little Falls, N J.	773	41	Oct. 1903
82	Youghiogheny River, Pennsylvania	782	58 9	Aug. 1888
83	Escanaba River, Escanaba, Mich.	800	13 4	. . . .

MAXIMUM OBSERVED FLOODS IN VARIOUS DRAINAGE BASINS. — (*Continued*)

Compiled from paper "Flood Flow Characteristics" by C. S. Jarvis in Trans. Am. Soc. C. E. 1926

	River and locality	Drainage area, sq. mi.	Discharge cu sec ft per sq. mi.	Date
84	Hudson River, North Creek, N. Y.	804	37 3	Mar. 1913
85	Raritan River, Bound Brook, N. J.	806	64 5	Sept. 1882
86	Snake River, near Moran, Wyo	820	18 4	June 1918
87	Kettle River, near Sandstone, Minn.	825	7 1	. . 1912
88	Holston, South Fork, Bluff City, Tenn.	828	39 8	. . 1902
89	James, North Fork, Glasgow, Va.	831	44 8	. 1896
90	Potomac, North Branch, Cumberland, Md.	891	22 8	1897
91	Schuylkill River, Reading, Pa.	900	89	. . 1850
92	Arkansas, Florence to Pueblo, Colo.	940	80	June 1921
93	Passaic River, Dundee, N. J.	981	20 2	Dec. 1878
94	Redwater River, Belle Fourche, S. Dak.	1006	8	. 1904
95	Hoosatonic, Gaylordsville, Conn.	1020	31	...
96	Scioto River, Columbus, Ohio	1047	80 8	Mar. 1913
97	Genesee River, Mount Morris, N. Y	1070	39.2	May 1894
98	Oconee River, Greensboro, Ga.	1100	62	Aug. 1908
99	Cowlitz River, Mossy Rock, Wash.	1170	43 5	Nov. 1906
100	Yuba River, near Smartville, Calif.	1200	92 5	Jan. 1909
101	Wenatchee River, Dryden, Wash.	1200	22.6	Dec. 1917
102	Lehigh River, Bethlehem, Pa.	1240	69.8	. . 1902
103	Thunder Bay River, Alpena, Mich.	1260	5 8	....
104	Chagres River, near Gatun, Panama	1320	93 9	......
105	Greenbriar River, Alderson, W. Va.	1344	46 5	Mar. 1913
106	Willamette, Middle Fork, Jasper, Ore.	1450	64 2	.....
107	Canadian River, French, N. Mex.	1480	105	Oct. 1909
108	Catawba River, Catawba, S. C.	1535	71 7	July 1916
109	Suwannee River, White Springs, Fla.	1600	9	Jan. 1908
110	Etowah River, Rome, Ga.	1800	33	Mar. 1906
111	Gallatin River, Logan, Mont.	1805	3 6	......
112	Black River, Carthage, N. Y.	1812	21 2	Apr. 1869
113	American River, near Folsom, Calif.	1900	99 5	Jan. 1862
114	Chemung River, Elmira, N. Y.	2055	67 1	June 1889
115	Flambeau River, Ladysmith, Wis.	2120	6	......
116	Androscoggin, Rumford Falls, Me.	2320	23 8	Apr. 1895
117	Susquehanna, Binghamton, N. Y.	2350	26.6	Mar. 1902
118	Colorado (Grand), Kremmling, Colo.	2360	9	June 1912
119	Menominee, near Iron Mountain, Mich.	2415	6 2	......
120	Miami River, Dayton, Ohio	2450	100	Mar. 1913
121	Tittabawassee, Freeland, Mich	2461	20 1	Mar. 1919
122	Wisconsin River, near Merrill, Wis	2630	8	.....
123	Saline River, Beverly, Kans.	2730	5 9	. . . 1896
124	Canadian River, Taylor, N. Mex.	2832	32.1	Oct. 1904
125	Kennebec, Waterville, Me.	3030	49 5	Dec. 1901
126	Connecticut, Orford, N. H.	3100	18 5	Mar. 1913
127	Iowa River, Iowa City, Iowa	3140	11 5	June 1918
128	Juniata, Newport, Pa.	3480	84	Mar. 1902

MAXIMUM OBSERVED FLOODS IN VARIOUS DRAINAGE BASINS. — *(Continued)*

Compiled from paper "Flood Flow Characteristics" by C. S. Jarvis in Trans. Am. Soc. C. E. 1926

	River and locality	Drainage area, sq. mi.	Discharge cu. sec ft per sq. mi	Date
129	Dan River, Clarksville, Va.	3749	8.8	July 1896
130	Merrimac River, Lowell, Mass.	4085	19.8	
131	Cape Fear River, Fayetteville, N. C.	4493	25.6	Aug 1908
132	Mississippi, above Sandy River, Minn.	4510	2.1	Sept. 1900
133	Merrimac River, Lawrence, Mass	4553	20.3	Apr 1852
134	Arkansas, Pueblo, Colo before 1914	4600	2.4	May 1901
135	Arkansas, Pueblo, Colo after 1920	4600	22.3	June 1921
136	Potomac River, Dam No 5, Maryland	4640	22.2	
137	Willamette River, Albany, Ore	4860	62.2	1861
138	Black Warrior, Tuscaloosa, Ala.	4900	38.8	1895
139	Chippewa River, Chippewa Falls, Wis.	5300	12.1	June 1905
140	Monongahela, Lock No 4, Pa	5430	38.1	1888
141	Yakima River, Kiona, Wash.	5520	11.5	Nov. 1906
142	Susquehanna, Williamsport, Pa.	5670	61.7	1889
143	Salt River, Roosevelt, Ariz	5756	36	Mar. 1893
144	Delaware, Riegelsville, N. J	6430	44.3	Oct. 1903
145	Penobscot, West Enfield, Me	6600	23.2	May 1923
146	Delaware, Lambertsville, N. J.	6855	37.1	Jan. 1841
147	Little River, Cameron, Tex.	7010	92.3	Sept. 1921
148	Savannah River, Augusta, Ga	7500	40	Sept. 1888
149	Connecticut, Sunderland, Mass.	7700	13.4	May 1854
150	Connecticut River, Holyoke, Mass.	8660	21.1	May 1854
151	Colorado (Grand), Palisade, Colo.	8790	6	June 1921
152	Tennessee River, Knoxville, Tenn.	8990	17.5	Mar. 1902
153	Allegheny River, Kittanning, Pa.	9010	29.9	Mar. 1913
154	Potomac, Point of Rocks, Md.	9654	33.7	June 1889
155	Susquehanna, Wilkes-Barre, Pa.	9810	22.1	Mar. 1902
156	Susquehanna, Danville, Pa.	11,100	27.4	Mar. 1902
157	Potomac, Great Falls, Md.	11,427	28.4	June 1889
158	Canadian River, Logan, N. Mex.	11,440	12.3	Oct. 1904
159	Mississippi, Sauk Rapids, Minn.	12,400	4.1	....
160	Colorado (Grand), Fruita, Colo.	17,100	7	July 1884
161	Mississippi, Anoka, Minn.	17,100	2.87	. .
162	Ohio River, Pittsburg, Pa.	19,100	22.98	 1907
163	Tennessee River, Chattanooga, Tenn.	21,382	34.37	Mar. 1867
164	Ohio River, Wheeling, W. Va	23,800	21.30	Feb. 1884
165	Susquehanna, Harrisburg, Pa.	24,030	30.60	June 1889
166	Red River, Grand Forks, N. Dak.	25,000	1.70	 1897
167	Susquehanna, McCall's Ferry, Pa.	26,766	25.1	Mar. 1904
168	Rio Grande, San Marcial, N. Mex.	30,000	1.10	Oct. 1904
169	Tennessee River, Florence, Ala.	30,800	16.2	Mar. 1897
170	Colorado River, Austin, Tex.	34,200	3.57	Apr. 1900
171	Mississippi, St. Paul, Minn.	36,085	3.32	Apr. 1881
172	Kansas River, Lawrence, Kans.	59,841	3.80	.. 1903
173	Mississippi, Clayton, Iowa	79,040	2.66	. . 1880

MAXIMUM OBSERVED FLOODS IN VARIOUS DRAINAGE BASINS. — (*Concluded*)

Compiled from paper "Flood Flow Characteristics" by C. S. Jarvis in Trans. Am. Soc. C. E. 1926

	River and locality	Drainage area, sq. mi.	Discharge cu. sec ft per sq mi	Date
174	Ohio, Louisville, Ky	90,600	8 5	Mar. 1913
175	Red River, Arkansas	97,000	2 32	. . .
176	Colorado, above Gila Junction, Ariz.	169,000	89	1909
177	Mississippi, Grafton, Ill.	171,570	2 10	1883
178	Rio Grande, near Rio Grande, Tex.	220,000	91	1872
179	Colorado, below Gila Junction, Ariz.	225,000	1 05	Jan 1916
180	Ohio River, Cairo, Ill.	233,000	6	Mar. 1913
181	Niagara, Niagara, N. Y.	263,440	1 13	.
182	St. Lawrence, near Ogdensburg, N. Y.	298,080	1 07	. .
183	Mississippi, St. Louis, Mo.	702,380	1 28	1883
184	Mississippi, Cairo, Ill.	902,900	2 23	1912
185	Mississippi, Helena, Ark.	1,000,000	2 04	. .. 1912
186	Mississippi, Carrollton, La.	1,400,000	1 07	May 1922

On some of the drainage basins given in the above table by Jarvis, the watershed characteristics and effective contributing area so overshadow the influence of size of total tributary area that the latter is indiscernible.

The magnitude of many of the floods reflects unusual rainfall conditions on the drainage basin more than total area of basin or watershed characteristics. This is particularly true of such floods as Nos. 3, 13, 18, 29 and 38, for example.

A determination of probable flood flow in a given stream can often be made with greater accuracy through the study of watershed characteristics and probable magnitude and frequency of the rainfall to be expected on the basin than through a study of observed stream flow from various watersheds. Neither study can be disregarded if a safe basis for construction is desired. On the other hand, although the magnitude of the Pueblo flood of 1921, for example, was ten times that observed before 1914, it would be financially impracticable to construct works in *all* streams so designed as to safely pass ten times the largest flood observed during ten or fifteen previous years of record.

Pettis Flood Flow Formula. — The latest formula devised for estimating flood flow is that just published by Major C. R. Pettis.* This formula is designed for use on unregulated basins having an area of not less than 1000 and not more than 10,000 sq. mi. For floods recurring, on an average, once in 100 years, the formula is

$$Q = 328\ PW^{\frac{5}{4}}$$

in which

Q = the maximum flood discharge in cu. sec. ft.

P = the maximum rainfall, in inches depth, to be expected on the basin within a period of six days, once in 100 years.

W = the average width of the drainage basin as determined by dividing the area of the basin by the length of the stream, neglecting minor sinuosities.

The novel feature of this formula is the emphasis it places on the width of the drainage basin as the one flow-determining factor, aside from rainfall. For streams draining basins of the area stated, this formula gives results that differ very little from the actual discharges observed on some fifty streams tabulated in the publication referred to.

Since the length of a drainage basin may be represented by a constant " K " times the width " W," the area may be represented by KW^2. It follows that $A^{.625} = (KW^2)^{.625}$ or $CW^{\frac{5}{4}}$.

Apparently, for all basins of the same ratio of width to length the Pettis formula is equivalent to the formula $Q = CA^{.625}$ in which the coefficient combines rainfall amount and frequency, and all other watershed characteristics. The Pettis formula, however, has been applied with equal success to basins, of the area stated, ranging from twice as long as they are wide, to others which are about nine times as long as they are wide. This is the distinctive contribution of the new formula.

* A New Theory of River Flood Flow, by Charles R. Pettis, Major Corps of Engineers, U. S. Army, Baltimore, Md. 1927.

DATA RELATING TO SOME OF THE MOST SEVERE FLOODS

Summer Floods on Small Watersheds

Cane Creek, N. C., Flood. — Cane Creek has a slope of about 150 feet per mile, and drains an area of about 22 square miles of rough, mountainous country, with much bare rock and, on the whole, very thin soil cover. The slope of the stream bed is so steep that the ordinary flood rise at Bakersville is only about five to six feet. During the flood of May, 1901, however, there was a rise of twelve feet. The flood plain of about 250 acres of high-grade agricultural land lying just above the town was swept clear of soil down to the rock. Boulders from four to twenty tons in weight were moved from 100 to 300 feet.

The precipitation which caused this flood amounted to about eight inches in 24 hours, resulting in a discharge estimated at 29,500 c.f.s. or 1341 c.f.s. per square mile.

In a number of places on the watershed there occurred what are locally known as "water spouts." Percolating water saturated the soil overlying the rocks, and when sufficient head had accumulated the water burst out, carrying earth, trees, etc., with it, and cutting great gashes down the hillsides.

Heppner, Oregon, Flood. — The Heppner, Oregon, flood occurred on June 14, 1903, on a small watershed of about 20 square miles, tributary to Willow Creek, in Oregon. The slope of the creek below Heppner is about 35 to 40 feet per mile. The flood was caused by excessive precipitation which lasted only about one-half hour. The storm area was about two to four miles in width and eight to ten miles in length. Such tremendous quantities of hail fell during the storm that five days later bodies were found well preserved in drifts of hail. Although there is no record of the exact size of the largest hailstones, some were found in the debris after five days which measured five-eighths inch in diameter. The hail was of a clear, practically transparent, ice.

The flood crest appeared at Heppner almost coincidently

with the first water and the creek was normal again in about $1\frac{1}{2}$ hours. The flood apparently traveled at a rate of about six miles per hour. One third of the town was entirely swept away, and out of a population of 1400, about 200 were drowned.

Monterey, Mexico, Flood. — Throughout the arid and semi-arid region, torrential rains over small areas are the cause of most extreme and disastrous floods on small streams. The worst flood on record, of this character, is that which occurred at Monterey, Mexico, on August 27, 1909. This flood occurred on the Santa Catarina River, which is dry about 350 days out of the year. The river drains a fan-shaped area of 544 square miles, varying in elevation from 7,820 feet in the headwaters to 1,766 feet in the city of Monterey. Most of the watershed is rocky, barren, precipitous, and free from plant growth of all kinds.

During August, 1909, two great floods occurred on this watershed, as the result of excessive precipitation. The first and smaller flood occurred between August 9 and 10. It was nevertheless the greatest flood since 1881. This flood followed the greatest drought in 30 years. From January, 1909, to August 9 of that year, only eight inches of rain had fallen, and during the previous year the entire precipitation had amounted to only ten inches. During the flood of August 9 to 11, 13.38 inches of rain fell in 42 hours. From midnight to noon, August 10, 3.50 inches fell; from noon on the tenth to 8 A.M. on the eleventh, 7.11 inches; from 8 A.M. to 6 P.M. on the eleventh, 2.77 inches; or a total of 13.38 inches in 42 hours. Of this, 10.61 inches fell in 30 hours. The result was a flood that would have been considered record-breaking had it not so soon been followed by a still greater one. Notwithstanding the heavy precipitation and the heavy runoff during this first flood of August 10 to 11, the river was dry again a few days later.

The flood of August 10 was followed by 21.61 inches of rain in 98 hours from 4 P.M. August 25 to 6 P.M. August 29. The distribution of this precipitation between August 25 and

29 is shown in Fig. 239. The crest of the flood occurred at 11 P.M. on August 27 after substantially 10 inches of rain had fallen at Monterey. It is probable, however, that the record of precipitation in the valley at Monterey is not a correct measure of the precipitation over the headwaters of the stream. Otherwise, the flood crest should have occurred about noon on August 28, after over 15 inches of rain had fallen.

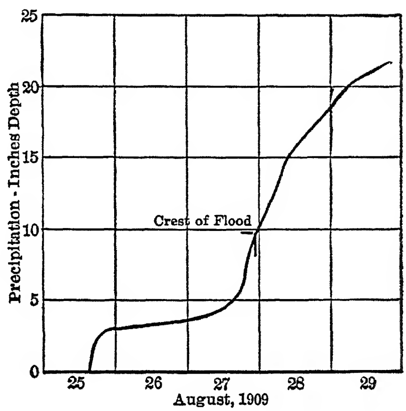


FIG. 239.—Precipitation during flood at Monterey, Mexico, on August 27, 1909.

The normal August precipitation at Monterey is 3.54 inches, and the normal for September is 4.28 inches. The mean annual precipitation for 21 years was 19.86 inches, yet, in the one month of August, 1909, 34.99 inches of rain fell.

The maximum discharge was estimated by Conway * as 271,500 c.f.s. or 590 second-feet per square mile. On a small adjoining watershed of $3\frac{1}{2}$ square miles, the observed runoff was 2900 c.f.s. or 825 c.f.s. per square mile.

During this flood, 452 acres of the city of Monterey, Mexico, were completely destroyed and about 5000 lives lost. Considerable flood damage also occurred in other parts of Mexico during August and September, 1909.

* Conway, G. R., Engineering News, September 23, 1909, Vol. 62, p. 315.

Winter and Spring Floods on Large Streams

Lower Mississippi River Floods. — The total watershed area drained by the Mississippi River system, shown in Fig. 240, is 1,240,050 square miles. The area above St. Louis is 165,900 square miles. The Missouri River drains an area of 527,150 square miles; the Ohio 201,700 square miles; and the Arkansas drains 186,300 square miles.

While the drainage area of the Ohio River is less than four tenths that of the Missouri River, the precipitation over the Ohio River watershed is so much greater than that over the Missouri as to result in a maximum flood discharge of 1,400,000 second-feet from the Ohio River as against 900,000 second-feet from the Missouri. The flood discharge of the Arkansas and the upper Mississippi above St. Louis amounts to 450,000 second-feet each, and that from the Red River to 220,000.

The distance, by river, from the source of the Mississippi in Lake Itasca, Minnesota, to its mouth in the Gulf of Mexico, is 2446 miles.*

The distance from the headwaters of the Missouri to the Gulf is still greater. On account of these great distances which the water must travel, and the great area of the watershed tributary to the main stream, excessive local rains have no effect on the floods of the lower Mississippi, except, perhaps locally, for a few hours, as happened on May 10, 1912. As the river was just cresting at New Orleans in this case, 7 inches of rain forced the crest up about a foot for a few hours.

The Rains Causing These Floods. — General rains extending over several weeks, at least, are required to produce great floods in the Mississippi between Cairo and New Orleans. Any one of the larger lower tributaries of the Mississippi is capable of producing a serious flood in all years of more than normal winter and spring precipitation, but the Ohio River is the principal flood-producing tributary. The effect of the

* Annual Report, Chief of Engineers, U. S. Army, 1909, p. 2677.

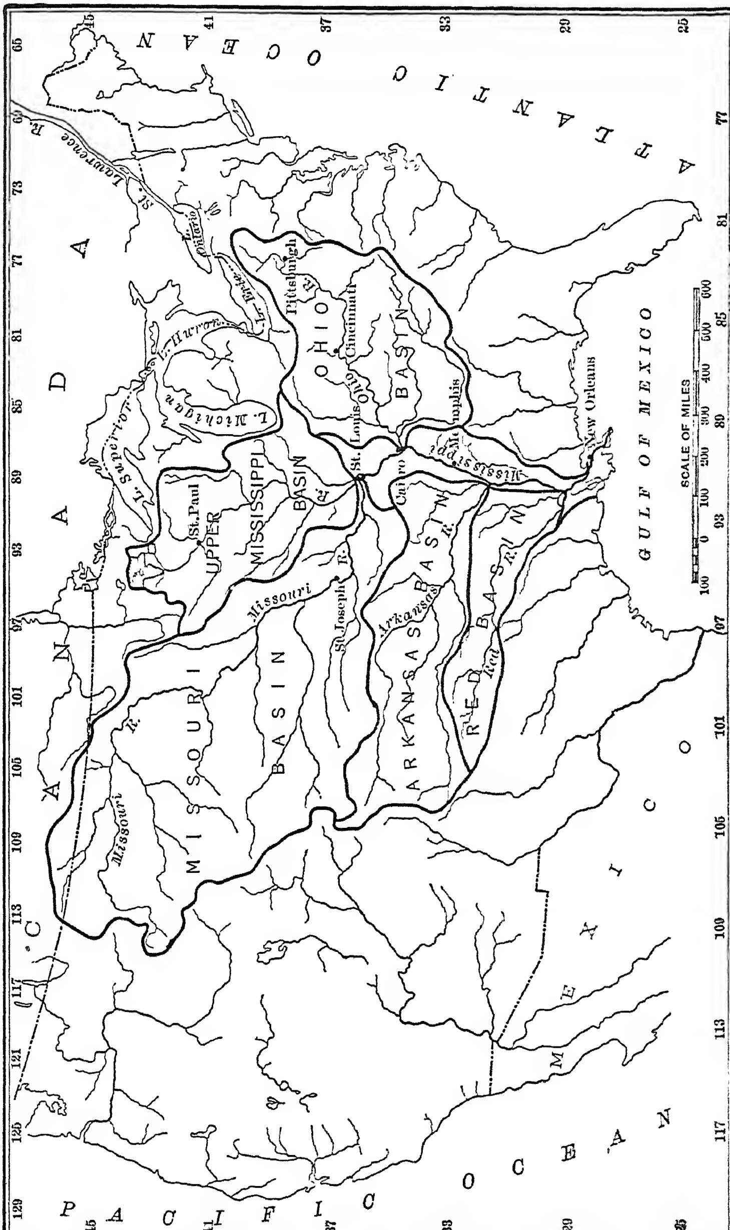


FIG. 240. — Mississippi River Drainage System. Total Area, 1,240,050 sq. mi.

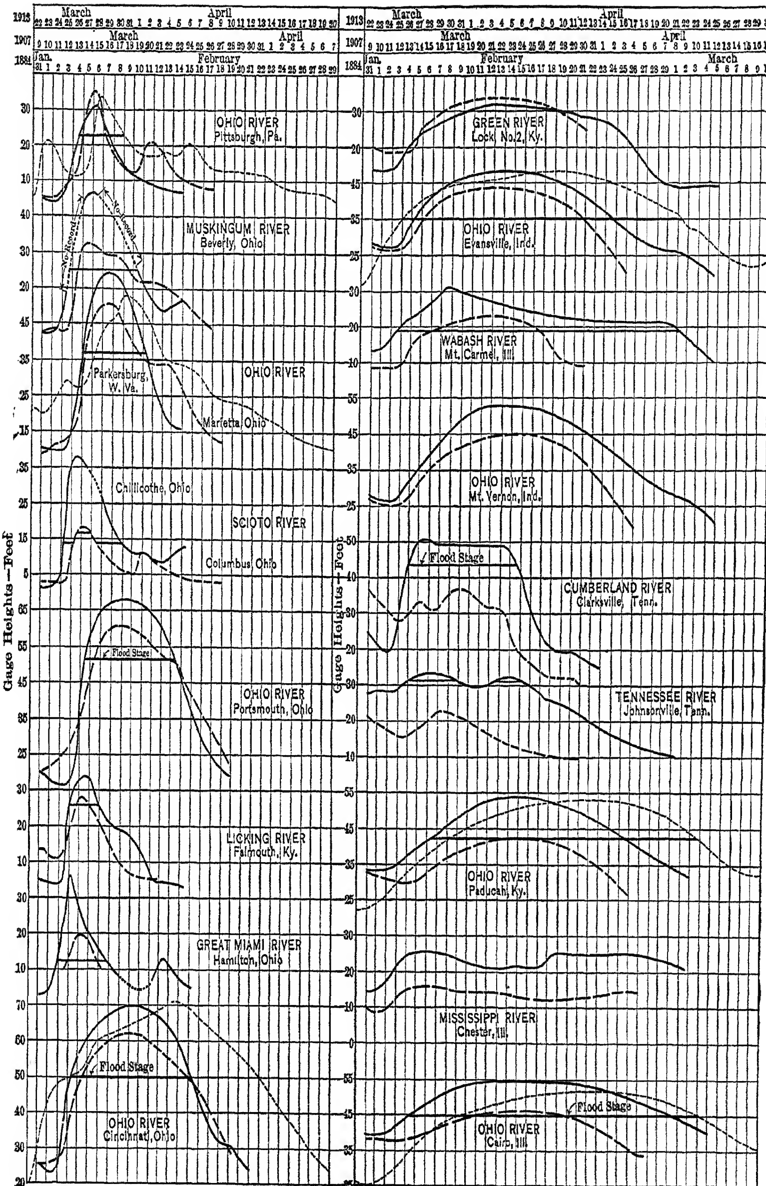
Ohio River is well shown by the fact that the maximum discharge of the Mississippi River, below the mouth of the Ohio, is 2,000,000 second-feet and below the mouth of the Red it is only 300,000 more, as a rule. In 1927 it was about 800,000 more.

The ordinary winter and spring precipitation in the Gulf region is usually ample to bring the lower river to an ordinary flood stage. If, under such conditions, several successive rainstorms, originating in the Southwest, pass over Texas and up the Ohio Valley, a serious flood will usually result on the lower Mississippi. As the upper Mississippi usually crests later than the Ohio, its principal effect is to prolong the floods on the lower reaches of the Mississippi. At New Orleans the flood crest is so flat as to show only about 1 foot variation in 30 days.

Flood Damage. — Floods occur on the lower Mississippi with great frequency, the average being about one every six years. In general, flood frequency increases with watershed area, although shape of area and other conditions frequently nullify the usual relationship. The duration of the flood stages on the lower Mississippi is from 30 to 60 days, and as the flood crest is usually reached late in the spring, the damage to agricultural lands is aggravated. As the flood crest occurs at continually later dates between Cairo and the Gulf, and as spring occurs continually earlier with decreasing latitude, the interference of flood water with agricultural pursuits becomes increasingly more important toward the South.

Flood losses in the lower Mississippi and Ohio River valleys, in 1912, were estimated at over $75,000,000 and in 1913 at over $150,000,000. The area flooded between Cairo and the Gulf, in 1912, was about 12,000 square miles. The Federal Government fed 272,753 refugees and 50,000 cattle during the 1912 flood. 352 miles of the St. Louis, Iron Mountain & Southern Ry. was under water — some of it for over five months.

Ohio River Floods. — Floods of great magnitude, on the main water course of a large drainage basin, seldom result from summer rainfall. Floods on the tributaries are not necessarily syn-



Data from U.S.G.S. Water Supply Paper No. 334

COMPARATIVE FLOOD HYDROGRAPHS

OHIO RIVER AND PRINCIPAL TRIBUTARIES

1913 FLOOD
1907 FLOOD
1884 FLOOD

Fig. 241.

chronous with floods on the main stream. Excessive summer rains may produce extreme flood conditions on the minor tributaries of the Ohio River, but all the great floods on the main stream have been the result of winter or early spring precipitation or of a combination of both.

The precipitation over the Ohio River valley occurs rather uniformly distributed through the year, averaging about $3\frac{1}{2}$ inches per month. The winters are mild. The mean monthly temperature over the greater portion of the watershed ranges from about 25 to 35 degrees, and the mean annual temperature from 50 to 60 degrees. Sufficient snow accumulates, however, when the winter months are colder than usual, to be an important factor, in conjunction with heavy spring rains, in producing flood stages in the streams.

The Ohio valley lies almost directly in the path of, or on the side of heaviest precipitation of, most of the cyclonic storms which cross the country from the West and pass out by way of the St. Lawrence River valley. A fortunate circumstance, which somewhat reduces the height of floods on the main stream and certainly reduces the frequency of serious floods, is the fact that the river flows in the opposite direction to that traversed by the storms which bring precipitation to this basin. (No alarm need be felt that these storms will ever become reversed in direction!) This permits a large portion of the discharge from the lower tributaries to get away before that from the upper tributaries arrives in the lower reaches of the stream.

Comparative Flood Hydrographs. — None of the great Ohio River floods of the past set the high-water mark along the entire length of the river from Pittsburgh to Cairo. The 1913 crest set a new mark from St. Marys to Maysville and also from Mt. Vernon to Cairo. The 1884 flood still holds the record at Wheeling, Cincinnati, Louisville and Henderson. Comparative flood hydrographs for the Ohio River and its principal tributaries, for the floods of 1884, 1907 and 1913, are shown in Fig. 241. The gage height corresponding to flood stage is shown by a heavy line.

Flood of 1884. — The flood of February 4 to 15, 1884, was caused by the combination of heavy rain and melting snow. January, 1884, was cold, and heavy snow fell in the mountains. The ground was frozen over a large portion of the upper watershed when the warm spell set in. This caused the river to reach virtually flood stage before the rains began. An average of only three to five inches of rain fell over the watershed during the eleven days from February 4 to 14. The accumulated snowfall, however, rapidly melted when the temperature rose to about 60 degrees on February 5. Melting snow, combined with the moderately heavy precipitation, produced record flood stages on portions of the main stream. The large quantity of water delivered by the 1884 flood is well shown by the hydrographs of Fig. 241.

Floods of 1913. — The floods of March, 1913, resulted, primarily, from excessively heavy, uniformly distributed precipitation over almost the entire watershed. There was practically no frost in the ground anywhere on the watershed, but the soil was pretty well saturated. The precipitation over the entire watershed of 203,000 square miles, between March 23 and 27, averaging 4.86 inches, is shown in Fig. 220. Two storms from the Southwest followed each other so rapidly as to practically become one. The path taken by these storms is indicated by the elongated area of equal rainfall shown in Fig. 220.

The time interval involved in the passage of the storm up the valley is well illustrated by the profile of the water surfaces of the Ohio River, on March 25 and 27, Fig. 242. This figure also shows the flood crests at various points on the main stream and on its most important tributaries.

The Great Miami River crested at Hamilton early on the twenty-sixth. The Scioto crested at Chillicothe about noon of the twenty-sixth and discharged its flood water into the Ohio, at Portsmouth, about a day later. The Allegheny, the Muskingum, and the Licking crested on the twenty-seventh. The Monongahela, the Kanawha, the Big Sandy, the Kentucky, and

the Cumberland crested on the twenty-eighth, while the main stream at Cairo did not crest until April 4.

The effect of the passage of the rainstorm up the valley is well shown by the fact that the Great Miami caused a rise on the Ohio, 21 miles above the mouth of the Miami, at Cincinnati, to nearly flood stage, before the Ohio at Portsmouth, at the mouth of the Scioto, had barely started to rise.

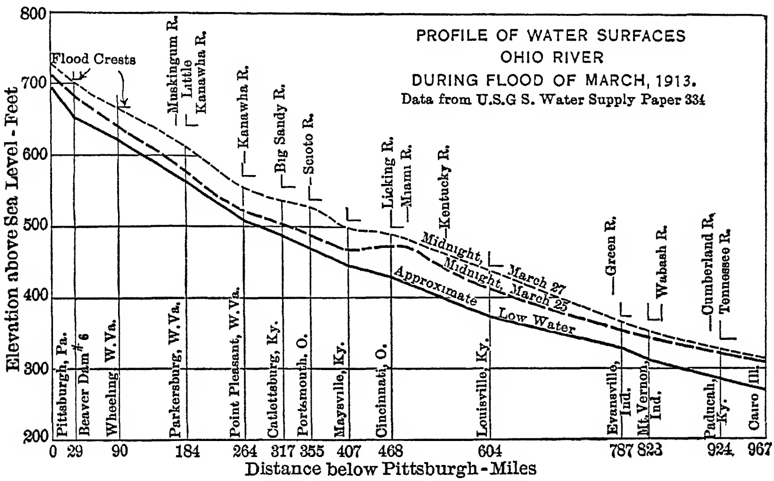


Fig. 242.

The profile of water surfaces, Fig. 242, shows that the water level in the Ohio, on the night of the twenty-fifth, was higher at Cincinnati than at Maysville, sixty-one miles up river. Under these conditions the current, of course, was upstream or negligible, and the river channel acted as a reservoir. This condition prevailed for about thirty-six hours.

The rapid rise of the Ohio at Portsmouth on the twenty-seventh was caused by the discharge from the Scioto.

Seine River, Paris, Flood. — The flood on the Seine River at Paris, France, in February, 1910, was the second greatest flood in the history of this stream, which dates back over 250 years. The area of the watershed is 30,370 square miles, and the flood discharge was about 83,500 second-feet. The river

rose about 28 feet as the result of steady rains during December, January and February, amounting to about $8\frac{1}{2}$ inches, as against an average precipitation, during the same period, of about $4\frac{1}{2}$ inches. A large part of the January precipitation fell as snow, particularly in the mountains of the Yonne district. The ground was practically saturated and the water-table high. About January 15, a thaw and rain set in which quickly brought down a large portion of the accumulated snowfall. January 21 to 22, a cold spell in the mountains temporarily held back what snow still remained. The crest of the flood came on January 28, when the warm weather and rain brought the waters from the two main tributaries of the Seine to Paris at the same time.

The greatest recorded flood on the Seine River occurred on March 1, 1658, when the stage rose to about 15 inches above the 1910 crest. The next greatest flood occurred in 1740 when a maximum stage about $1\frac{1}{2}$ feet below the 1910 crest was reached. Between 1800 and 1900, eight floods occurred during which the stage rose within less than ten feet of the 1910 crest.

LOW-WATER FLOW OF STREAMS

The low-water flow of streams, particularly where facilities for storage are absent, is at once the most important among stream-flow data and the most difficult to ascertain. On few streams of the country have records been taken sufficiently long to give a dependable value for low-water flow. By careful analysis, however, of the precipitation, temperature, and other conditions that surrounded the lowest recorded discharges, a reasonably good estimate of probable future extreme and ordinary low-water flow can be made.

Effect of Precipitation. — A combination of hydrological conditions is usually the cause of low water, but deficient or ill-timed precipitation is the predominant one. On streams in the arid and semi-arid region, and also on many small streams

in other parts of the country, that are dependent upon surface runoff for their low-water supply, low discharge accompanies or immediately follows the period of deficient precipitation. On streams fed mainly by ground-water, on the other hand, the low-water flow is determined by the precipitation several months previous. Streams fed by melting snows are also dependent upon precipitation that fell long before the low-water stage is reached. The low discharge of these streams is also influenced by the rate of melting of the snow and the evaporation loss during the winter and spring.

Effect of Ground-water Supply. — The low-water discharge of most streams in the United States consists of seepage flow derived from the ground-water supply. While this supply may be ample in early spring, its adequacy for the maintenance of a good low-water flow during the summer is dependent very largely upon the evaporation and transpiration draft upon ground-storage later in the season. This draft on storage is dependent, primarily, upon the depth to the water-table. If the level of saturation is about twenty feet below the surface of the ground in clay subsoils, and about ten feet in sandy subsoils, and if the watershed is free from matured forest cover, the ground-water supply is safe against evaporation and transpiration loss, and against the effects of deep freezing, and the low-water flow of the streams is dependent upon the amount of the ground-water supply at the beginning of the dry season and the character of the saturated subsoil. If the subsoil at the level of saturation is sand, the ground-water supply available for the maintenance of stream flow, for any given depth to the water-table, is from two to three times that which is available if the subsoil is clay. The best ground-water supply is found in regions of ample precipitation where both soil and subsoil are of fine, sandy character and forest cover is absent.

Lake and Swamp Storage. — The extent to which, on a given precipitation, a natural lake will sustain stream flow

during dry weather is dependent mainly upon its depth, as this determines its surface temperature and, consequently, the evaporation loss. This one factor usually quite over-shadows the effects of all others. However, a narrow outlet and small fluctuations in stage are usually indications of well-equalized outflow, but of relatively small, tributary drainage area. Large fluctuations in stage usually indicate a large tributary drainage area and a relatively narrow outlet.

During dry weather, the evaporation loss from all lakes is very high, and if a lake is shallow, the low-water outflow may be reduced to zero. Lake Milaca, at the headwaters of the Rum River in Minnesota, is an illustration of this condition. The watershed area above Onamia is 414 square miles, and the area of the lake is 207 square miles. The discharge from the lake during the 19 months from September, 1910, to March, 1912, following the hot, dry summer of 1910, amounted to only .21 inch in depth on the drainage area, and during both winters the discharge was zero. Lakes Traverse and Bigstone, and Red Lake, in Minnesota, are other relatively shallow lakes with small tributary drainage basins, whose low-water discharge is zero or substantially that.

Lake Superior, on the other hand, although it has a small tributary watershed, has such great depth that the temperature remains uniformly low throughout the year, with consequent reduction in evaporation loss, and a well-sustained low-water outflow.

Lakes located in the upper portion of a drainage basin usually have a small fluctuation in stage and are of much less benefit in equalizing stream flow than lakes in the lower portion of the basin. Ottertail Lake, in Minnesota, for example, located in the lower portion of the Ottertail watershed, though relatively small is, nevertheless, very effective in equalizing stream flow, although part of the equalization effected must be credited to the character of the tributary watershed.

Lake storage is usually not as effective in maintaining low-water flow during protracted dry spells as ground storage, but

it is always much more effective than swamp storage — in fact, swamp storage is distinctly detrimental to low-water flow, even though swamps do equalize the *ordinary* runoff. This fact is well illustrated by the Thief River, Minnesota, which has a drainage area of 1010 square miles, above Thief River Falls. The discharge of this stream was zero for 5 months from October, 1910, to February, 1911, and aggregated only .12 inch in depth on the tributary watershed during the two years from September, 1910, to August, 1912.

Effect of Temperature. — A sudden rise in temperature, in spring, sends most of the accumulated winter precipitation into the streams at once. A gradual rise permits much more percolation. Cold weather early in the fall, before snow has fallen, freezes the ground to such depths that later in the season, after the ground is covered with snow, the warmth of the earth underneath cannot thaw out the frozen ground, and hence winter percolation through the melting of snow from underneath, is impossible, thus reducing the ground-water supply. High summer temperatures greatly increase evaporation and thus reduce percolation and ground-water supply.

Low winter temperature, causing the formation of a heavy ice cover over streams and lakes, results in congealing a substantial amount of water, aggregating ten to twenty per cent of the winter yield of small watersheds.*

As the freezing often occurs very suddenly, six inches of ice cover forming in a few days, the reduction in daily discharge will be several times as great as the reduction in yield would indicate.

The formation of ice cover over lakes does not reduce the low-water outflow so long as the point of control, at or near the outlet, remains free from ice cover, because the effective head of water on the control section remains unchanged, the weight of the ice being exactly equal to the weight of the water congealed.

* See Hoyt, W. G., in U. S. G. S. Water Supply Paper, No. 337, p. 10.

When the water-table is close to the surface of the ground, as in the case of marshes and swamps, low winter temperature combined with an absence of snow, results in freezing the ground to depths of several feet and thus imprisoning all ground-water contained in this layer. Moreover, even if no gravity-water is frozen up, the lowering of the temperature of the moisture in the soil results in an increase in the surface tension and consequently in the amount of moisture held by capillarity. This causes a lowering of the water-table through upward movement of capillary water.

When the ground-water lies within the range of seasonal changes in ground temperature, winter weather will increase the viscosity of the water and reduce the rate of seepage flow by a substantial amount.

When the ground-water lies far below the surface of the earth it is entirely free from the last two of these temperature effects and the *yield* of the watershed is determined, primarily, by the ground-water supply. Even under such conditions, however, the daily rate of discharge of the streams draining such watersheds may be prominently affected by temperature changes. Some of the ground-water may be suddenly congealed in the river channels and the remainder may be retarded by the increased friction resulting from the ice cover. Of this remaining portion a substantial amount is stored in the river channel while the stage is being raised sufficiently to permit the flow of ground-water to be carried away through the increased cross-section necessitated by the increased friction resulting from ice cover. The effect of these temporary abstractions from stream flow is well illustrated by the data for the upper Mississippi River at Minneapolis, Fig. 243. About two inches of rain between November 23 and 28 had resulted in an increase of about 4000 second-feet in discharge. Before much of this rainfall had run off, however, a cold spell set in which sent the minimum temperature below zero. The result was a drop in discharge from 12,000 second-feet to less than 5000. This

was followed by a recovery to more than normal, indicating that not all of the November rain had had an opportunity to run off before the cold spell had set in. In November, 1906, moderately cold weather resulted in a reduction in discharge from about 11,500 second-feet to about 7000 second-feet. Warmer weather, with the minimum above freezing for two days, resulted in an increase in discharge to 10,500 second-feet. A return of cold weather was followed by a gradual reduction in discharge to about 8500 second-feet, when a cold wave, the first week in December, quickly sent the discharge down to less than 5000 second-feet. The river gradually recovered from this drop, and succeeding extremely cold spells had no further serious effect.

In 1909 the discharge increased until late November to about 7000 second-feet as the result of the melting of the heavy snowfall in the middle of the month. Then a cold wave that sent the *mean* temperature to about zero, reduced the discharge to 2500 second-feet. From this low mark the river gradually recovered and subsequent zero temperatures had little effect.

These data clearly show that in the case of the Mississippi River above Minneapolis, the principal temperature effect on the low-water flow is that which results in channel storage of large quantities of water while the stage is being raised to permit the normal discharge under the increased friction resulting from the rapid formation of ice cover and frazil. The secondary effects, those accompanying the second and third cold spells after the last thawing weather, are due to the congealing of water as the ice cover thickens. Temperature effects on the ground-water itself are no doubt limited to minor portions of the watershed area.

Observed Low-water Flows. — The most complete summary of low-water stream-flow data is that given by Kuichling in the New York State Barge Canal Report of 1901. These data are of some value in so far as the streams to which they

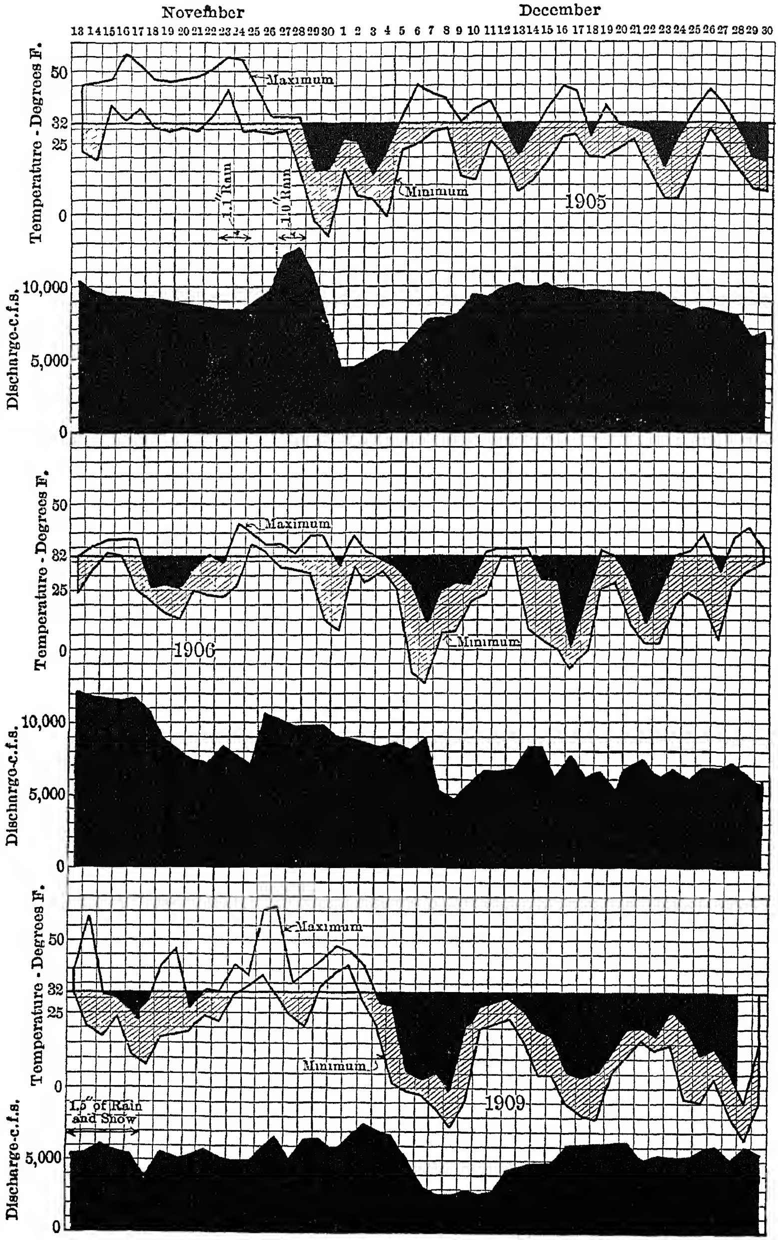


FIG. 243.—Effect of Temperature on the Low-Water Flow of the Mississippi River at Minneapolis, Minn.

refer are concerned, but can seldom be used in estimating the low-water flow of other streams, even in the same locality, because the watershed characteristics are practically never identical. Moreover, unless the hydrological conditions surrounding the observed low-water flows of these streams are known, little dependence can be placed on the data as they are no indication of the frequency with which the given low flows will probably be equaled, or even much lower flows experienced.

Valuable low-water stream-flow data for Minnesota streams, accompanied by pertinent, although somewhat incomplete, precipitation data, given by W. G. Hoyt in U. S. G. S. Water Supply Paper, No. 337, p. 14, are reproduced in Table 40.

The summer low-water flow of 1910 was due to exceptionally low precipitation — probably the lowest in the southeastern part of the State since the low-water period of 1864.

The winter low-water flow of 1911 to 1912 was caused by exceptionally low temperatures between Dec. 25, 1911, and Feb. 12, 1912, and deficient ground-water supply. The maximum temperature was below zero for 21 days during this period. Except for the fall precipitation being above normal the winter flow would undoubtedly have been still less. This is indicated by the winter flow of 1912–13, which in some streams was still lower than that of the previous year, because the fall precipitation was below normal even though the winter temperatures were about normal.

In endeavoring to interpret the data of Table 40 the author found that the July and August, 1910, minimum flow was not necessarily the minimum flow resulting from the deficient 1910 precipitation. On some streams the minimum occurred in the fall and winter of 1910, and on others the minimum of the summer of 1911 was actually less than the minimum of 1910, notwithstanding greatly increased precipitation. This condition undoubtedly resulted from deficient ground-water supply. The author believes that low winter temperature cannot produce abnormally low flows on streams where the

TABLE 40.—LOW-WATER FLOW OF MINNESOTA STREAMS (from U. S. G. S. Water Supply Paper, No. 337)

River	Station	Drainage area, square miles	Precipitation, April to July				Discharge, 1910, July or August	Precipitation, September to December				Discharge 1912, January or February	Precipitation, September to December			Discharge 1913, January or February	Flow
			Normal	1910	Difference	Per cent		Normal	1911	Difference	Per cent		1912	Difference	Per cent		
Hudson Bay drainage basin																	
Ottertail	Fergus Falls	1,310	13.70	6.06	− 7.64	0.44	32.6	5.92	6.28	+0.36	1.06	70	6.52	+0.60	1.10	77	Natural.
Pelican	"	433	13.70	6.06	− 7.64	0.44	5.6	5.92	6.20	+0.28	1.05	2	6.57	+0.65	1.11		"
Wild Rice	Twin Valley	805	13.25	5.56	− 7.69	0.42	21	6.59	5.32	−1.27	0.81	3	6.60	+0.01	1.00	9	Controlled.
Red Lake	Thief River Falls	3,450	13.50	5.50	− 8.00	0.41	236	6.50	5.10	−1.40	0.78	4	6.20	−0.30	0.95	85	Natural.
"	Crookston	5,320	13.08	5.46	− 7.62	0.42	293	6.41	5.05	−1.36	0.79	28				120	Controlled.
Clearwater	Red Lake Falls	1,310	11.18	5.43	− 5.75	0.49	35.7	5.53	5.43	−0.10	0.98	25	6.76	+1.23	1.22		Natural.
Littlefork	Littlefork	1,720	14.35	7.90	− 6.45	0.55	88.4	7.72	4.84	−2.88	0.63	70	6.75	−0.97	0.88	58	"
Bigfork	Big Falls	1,320	14.23	7.49	− 6.74	0.53	65.3	6.38	4.88	−1.50	0.77	30	6.87	+0.49	1.08		"
Vermilion	Below Vermilion Lake	507	14.70	8.30	− 6.40	0.56	.	8.20	7.30	−0.90	0.89	95	5.91	−2.29	0.72	100	"
Mississippi River drainage basin																	
Mississippi	Above Sandy River	4,510	13.97	7.94	− 6.03	0.57	1,915	7.20	5.68	−1.52	0.79	498	5.11	−2.09	0.71	544	Controlled.
"	Anoka	17,100	13.13	7.15	− 5.98	0.54	3,390	6.28	7.26	+0.98	1.16	2,330	4.04	−2.24	0.64	1,910	"
"	St. Paul	35,700	13.22	7.15	− 6.07	0.54	3,850	6.27	9.23	+2.96	1.47	2,700	4.02	−2.25	0.64	2,330	"
Crow Wing	Pillager	3,230	13.97	7.00	− 6.97	0.50	283	6.14	7.05	+0.91	1.15	340	4.28	−1.86	0.70	345	Natural.
Sauk	St. Cloud	815	13.02	6.64	− 6.38	0.51	42.6	6.00	7.99	+1.99	1.32	30	3.05	−2.95	0.51		Controlled.
Elk	Big Lake	615	13.98	6.70	− 7.28	0.48		6.53	8.89	+2.36	1.36	50	3.48	−3.05	0.53	65	Natural.
Crow	Rockford	2,520	12.85	6.66	− 6.19	0.52	58.5	7.21	11.04	+3.83	1.53	40	2.80	−4.41	0.39	45	"
Rum	Cambridge	1,160	13.98	6.70	− 7.28	0.48	84.2	6.53	8.89	+2.36	1.35	70	3.48	−3.05	0.53	58	"
Minnesota	Odessa	1,560	12.79	5.49	− 7.30	0.43	16.5	5.25	9.67	+4.42	1.84	4	3.16	−2.09	0.60	3	"
"	Montevideo	6,300	13.05	8.35	− 4.70	0.64	72.5	5.54	9.94	+4.40	1.79	15	2.92	−2.62	0.53	76	"
"	Mankato	14,600	13.51	7.71	− 5.80	0.56	253	5.66	10.56	+4.90	1.87	250	3.54	−2.12	0.63	131	"
Chippewa	Watson	1,940	13.51	8.01	− 5.50	0.59	12	5.44	8.69	+3.25	1.59	5	2.76	−2.68	0.51	2	"
Cottonwood	New Ulm	1,190	13.93	9.21	− 4.72	0.66	9.3	5.86	12.63	+6.77	2.16	15	3.92	−1.94	0.67	3	"
Kettle	Sandstone	825	14.50	7.00	− 7.50	0.48	71.1	9.27	10.09	+0.82	1.09	90	4.40	−4.87	0.47	40	"
Snake	Mora	422	14.04	6.34	− 7.70	0.45	37.5	8.82	10.50	+1.68	1.19	30	3.61	−5.21	0.41	23	"
Cannon	Welch	1,290	14.06	5.06	− 9.00	0.36	124	8.04	14.65	+6.61	1.83	310	5.46	−2.58	0.68	100	Controlled.
Zumbro	Zumbro Falls	1,120	14.61	4.54	−10.07	0.31	157	7.68	15.32	+7.64	2.00	242	5.82	−1.86	0.76	145	Natural.
Zumbro, South Branch	"	821	...	...	...	...	...	7.68	15.32	+7.64	2.00	165	5.82	−1.86	0.76	80	"
Root	Houston	1,560	15.44	4.65	−10.79	0.30	322	8.29	15.88	+7.59	1.92	400	7.12	−1.17	0.86	270	"
Root, North Branch	Lanesboro	647	15.44	4.65	−10.79	0.30	134	8.29	15.88	+7.59	1.92	150	7.12	−1.17	0.86	100	"
Cedar	Austin	425	15.43	5.25	−10.18	0.34	49.5	7.87	15.84	+7.97	2.01	45	7.06	−0.81	0.90	33	Controlled.

water-table lies so far below the surface of the ground as it does in the Root River valley, Minn., for example. Ground temperatures do not change at this depth and low-water flow is determined by ground-water supply and not by temperature. On other streams, such as the Crow River where the water-table lies nearer to the surface, the low-water flow during the winter of 1910–11 was less than during the cold winter of 1911–12, so that on this stream, too, the ground-water supply really seemed to be the controlling factor.

It is not the intention, here, to say that temperature does not affect the flow of streams *at all,* because the thicker the ice cover, the more water is held back and the smaller the discharge. Relatively, however, this effect is far less than the effect of such differences in ground-water supply as commonly occur. The difference between the thickness of the ice that forms over streams in an average year and in an exceptionally cold year probably does not affect the winter *yield* of a watershed by more than 5 per cent. The momentary effect of sudden cold spells, as indicated in Fig. 243, on the other hand, may reduce the flow to one-half or even one-third normal.

CHAPTER X

STREAM-FLOW DATA

Need for Data. — The increasing utilization of the flow of streams for water power, water supply, sewage disposal, and irrigation purposes, and the disposition of excess water has created a great need for an accurate determination of the physical quantities involved. The data required are not only the ordinary flow of a stream but its extremes of flow, and the variations in flow through the day, the month, the year, and through the cycle of dry and wet years.

How Data are Obtained. — Stream-flow data may be obtained directly, by the measurement of flow, or indirectly by computing runoff from such physical data as rainfall, temperature, and watershed characteristics. So far as possible, the actual flow of streams should be instrumentally measured, but when the data secured through such measurements cover only a few years and do not include the extremes of meteorological phenomena to be expected on the given watershed, such measurements may advantageously be extended by computations of flow based on physical data.

Current Meter Measurements

The method everywhere acknowledged as best adapted to an accurate determination of the discharge of practically all streams is that of determining the velocity of the water by means of a current meter and the cross-sectional area of the channel by means of soundings. By determining the relation between the stage of a stream, or the "gage height," and the amount of water flowing, or the "discharge," by means of meter measurements at various stages, and by obtaining either a con-

tinuous record, or frequent readings of the gage as circumstances may demand, a continuous record is secured of the discharge of the stream.

The Gaging Station. — The place on a stream at which gage heights are observed and where usually meter measurements are also made, is known as a "gaging station." The selection of a gaging station is one of the most important steps in obtaining accurate records of stream flow.

The ideal gaging station should possess the following characteristics:

1. It should be located just *above* a "point of control," that is, a place in the stream where the fall at all stages is greater than in the reaches just above and below.
2. It should offer a conveniently located and secure, sheltered spot for the gage and be readily accessible to the observer.
3. The channel of the stream should be stable and permanent, free from vegetation and not subject to overflow.

If the reconnaissance for the gaging station is made at low water, a good point of control can be more readily identified than at high stages. Provided the channel is permanent, a place in the stream that constitutes a point of control at low stages will also be a control at high stages if the channel is narrower than in the reach below or if the fall at the control is quite large.

On those smaller streams with continually shifting channel bed and banks, where the obtaining of accurate stream-flow records is essential, artificial controls must often be provided. These may consist of a concrete weir or a ridge of boulders carefully placed in the channel.

The Meter Section. — The cross section of the stream at which the velocity is measured is known as the meter section. This section may be a considerable distance either up or down

stream from the gaging station so long as no appreciable amount of water enters the stream in the intervening distance. It is not unusual for the meter section on a large stream to be located several miles from the gaging station.

The ideal meter section should possess the following characteristics:

1. The channel for some distance above and below the section should be reasonably straight and uniform in cross section, and the bed and banks should be smooth and regular.
2. The velocity should be reasonably uniform from bank to bank, and the water should move as near to stream lines as possible.
3. The mean velocity should, if possible, range somewhere between 2 and 6 feet per second.

It is often desirable to use different meter sections at different stages, so that for each stage the requirements of the ideal section may be as nearly attained as possible.

A permanent channel is not a necessity for the meter section although it is for the gaging station.

If the bed and banks are permanent, however, which is the case if the meter section is at the gaging station, the cross section of the channel can be fully developed by sounding below the water line and by level above this line. In developing the cross section a permanent point known as the "initial point," to which all distances across the stream are referred, is first established. Thereafter, when making meterings, merely the elevation of the water surface need be determined to secure the depths at the points where the velocity is to be measured, and the area of cross section.

Soundings in moderately deep water can best be made with a pole graduated to feet and tenths. For greater depths a weight attached to sash cord is satisfactory, although the possibility of shrinkage and stretching must be kept in mind. For great depths and swift water a heavy weight suspended by

wire is necessary. On the Lake Survey, in sounding fifty-foot depths, a 136-pound weight was used.

Distances on the cross section may be marked on the railing, when measurements are made from a bridge, or by a tagged line stretched across the river when measurements are made from a boat, or a cable car, or by wading. In case floating logs or boats, or great width of channel make the use of a tagged line impracticable, distances on the section may be determined by observing angles to a base line on shore, by means of a sextant. Under such conditions, and also when the channel is shifting, soundings must be taken each time a measurement is made. The distance between soundings is determined by the size and character of the stream and may be 2, 5, 10, or 20 feet.

The Staff Gage. — The gage most commonly used in determining the stage of the stream consists of a graduated scale from which the elevation of the water above an actual or an assumed datum is read directly. Such a gage may consist of a wooden staff painted and graduated into feet and tenths, or of a scale cut into masonry walls or piers, or of metal plates with figures enameled upon the face. The gage may be placed in either a vertical or an inclined position.

The zero of all gages should be referred to at least two bench marks of permanent character, located in the immediate vicinity of the gage and should be instrumentally checked at least once a year.

The Hook Gage. — The hook gage consists of an inverted, graduated rod with an upturned hook at the bottom. The rod slides in a groove to which a vernier may be attached for precise reading. This type of gage gives the most accurate determinations of water level but is used mainly in laboratory work.

The Chain Gage. — The chain gage consists of a weight which is lowered by a chain until it touches the surface of the water. The weight generally hangs supported over a pulley, the chain

being led horizontally over a graduated scale from which the readings are made. When placed out-of-doors, the chain, scale, and weight should be enclosed in a box. The length of the chain should be checked occasionally and necessary corrections applied to the readings. A chain gage may be advantageously used where logs, ice, or other floating debris would destroy a staff gage.

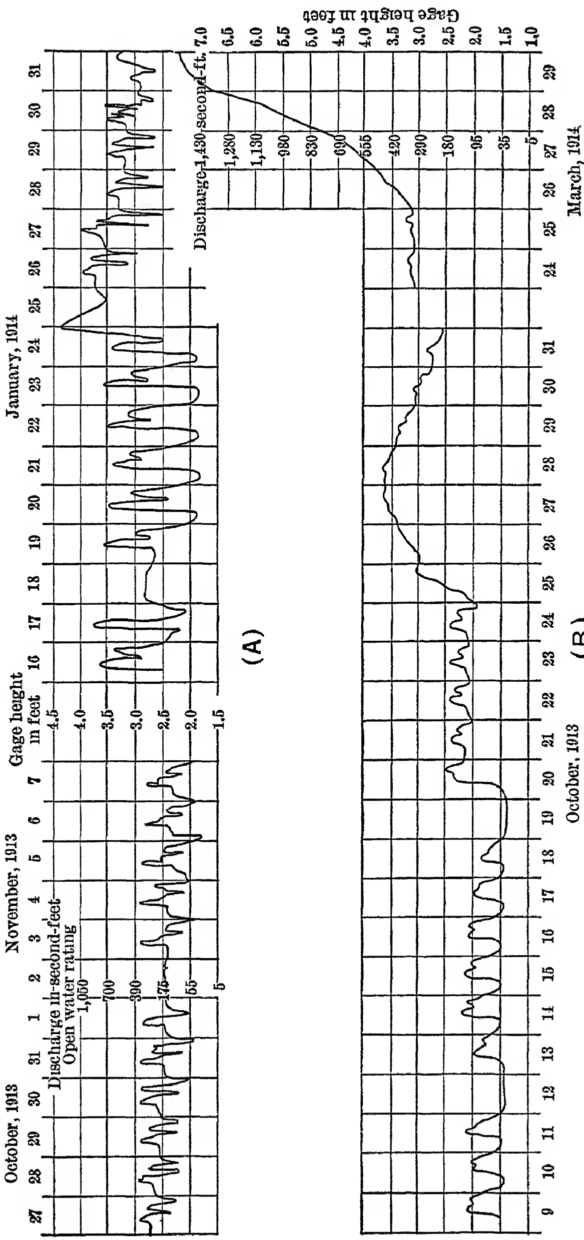
The Automatic Recording Gage. — The advisability of installing a recording gage depends, mainly, upon whether two or three readings of stage a day will be sufficient for obtaining the correct daily discharge of a stream. The conditions under which a continuous record of stage is often necessary and the installation of a recording gage desirable, are:

1. Rapid fluctuation in stage due to changes in the amount of water used by power plants, to log sluicing, or to the operation of diversion works on irrigation projects.
2. Rapid fluctuations in the stage of streams draining small watersheds, as the result of torrential rains or the sudden melting of snow.
3. Inaccessibility of gaging station or unreliability of observer.
4. Necessity for continuous records of flow for legal purposes.

Diagram A in Fig. 244 well illustrates the daily fluctuations in stage due to variations in the amount of water used by power plants. Under such conditions continuous records of stage are clearly necessary for the accurate determination of daily discharge.

Diagram B in Fig. 244 illustrates the reduced effect of power plant operation at medium and high stages when only a small portion of the stream flow is being utilized by the plant.

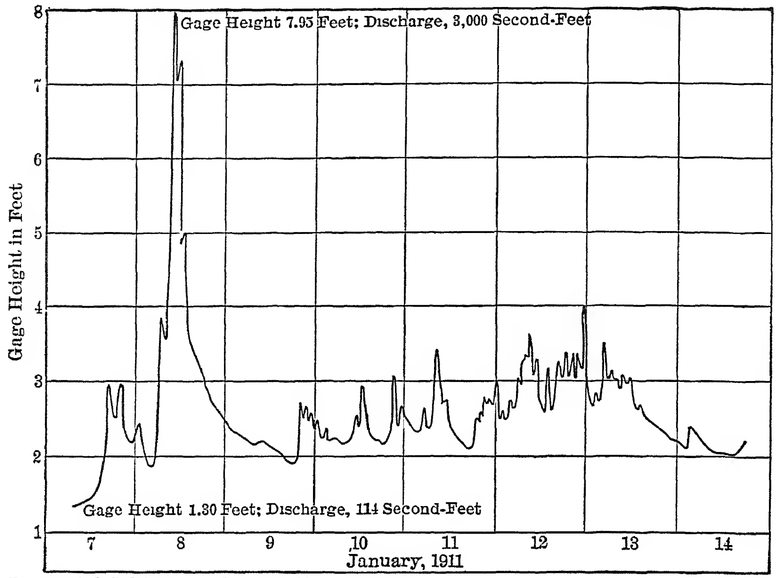
Fig. 245 illustrates the large fluctuation in flow occurring within a few hours on many small streams. On such streams morning and evening gage readings, only, would introduce gross inaccuracies into the resulting daily discharge.



From U.S.G.S. Water Supply Paper No. 375.

FIG. 244.—Effect of Power Plant Operation on Stream Flow.

A, Quaboag River at West Brimfield, Mass. B, Swift River at West Ware, Mass.



From U S.G.S. Water Supply Paper No. 375.

FIG. 245.—Rapid Fluctuations in Flow of Small Stream, North Fork of Wailua River Near Lihue, Kauai, Hawaii.

Fig. 246 shows the principal types of recording gages in use. The essential mechanical features of these gages are a float, and a chain belt connected to the float at one end and to a weight at the other end and carried up over a sheave which actuates a recording device that traces or prints the height of the float on a clock-operated record sheet.

The installation of a recording gage is well shown in Fig. 247. Staff gages for comparing the level of the water in the well with that in the river outside should always be installed, so that clogging of the intake may be immediately detected. The gage shelter should be well aired and camphor gum placed under the cover of the gage itself to help keep the record sheet dry. In cold weather a lamp or other heating device may be used to keep the gage from freezing up; or kerosene may be used in the float chamber, when this is not too large, and the difference in specific gravity between the kerosene and the water allowed for in gage reading.

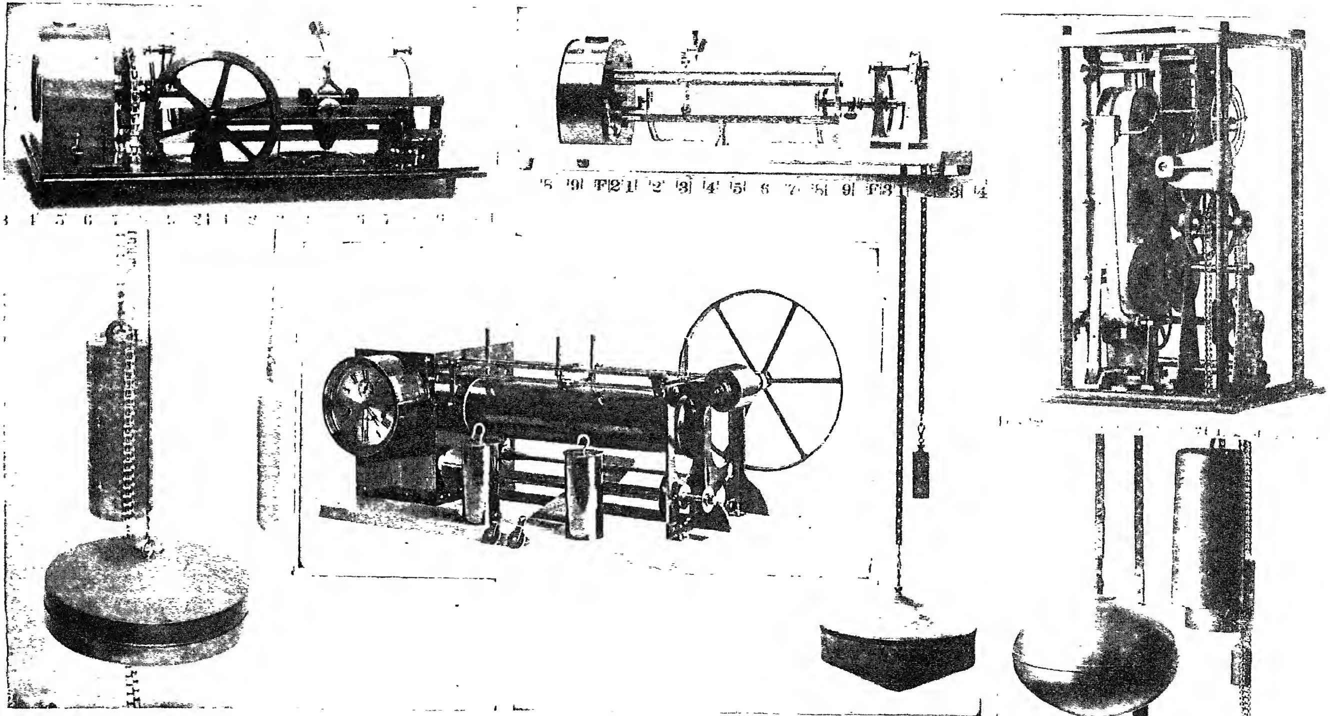
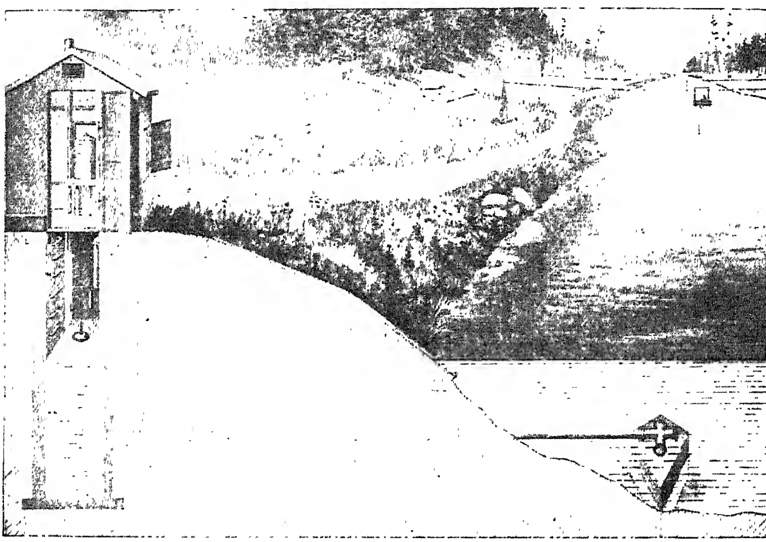


FIG. 246.—Recording Gages.

Recording gages are built to run from one day to 30 days or more. The most common kind is the seven-day gage.

As the discharge does not usually bear a straight line relation to the gage height, the mean daily gage height for a stream subject to great fluctuations in stage does not give the mean daily discharge. This must be based upon the mean hourly discharge corresponding to the observed mean hourly gage height.



From U.S.G.S. Water Supply Paper No. 384.

FIG. 247.—Typical Recording Gage Installation.

The Current Meter.—Although a considerable number of types of current meters have been used for measuring stream flow at various times in the past, the two in most common use today are the Price and the Haskell meters, illustrated in Figs. 248 and 249. The essential parts of both types of meters are a wheel revolved by the flowing water and a mechanism that reports the revolutions of the wheel to the observer.

The Haskell meter has a screw-propeller type of wheel mounted on a horizontal axis. The Price meter has a wheel consisting of several conical cups mounted on a vertical axis.

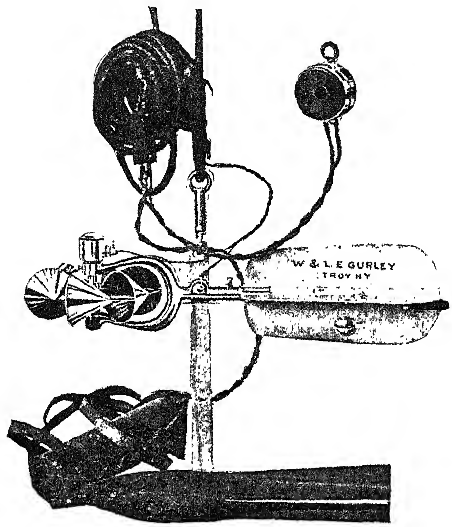


FIG. 248.—Small Price Current Meter with Telephone Sounder, Cable and Battery.

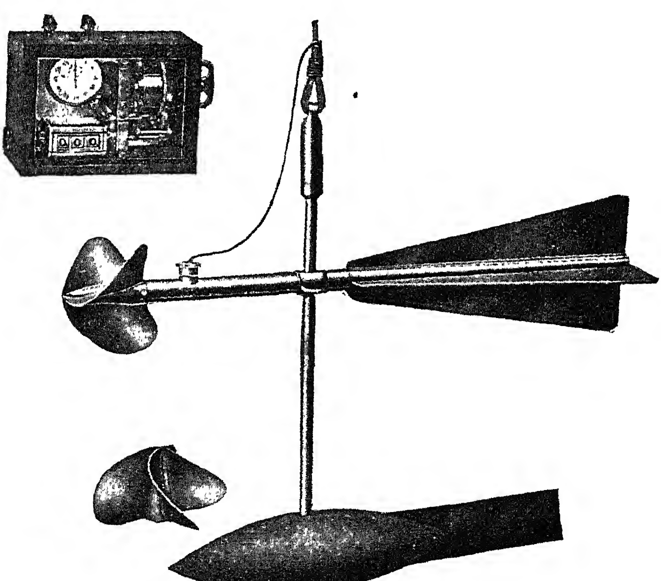


FIG. 249.—Haskell Current Meter and Register.

A small form of Price meter is used almost exclusively by the United States Geological Survey. The Haskell meter is extensively used by other departments of the Government. Both meters yield good results. The Price meter is lighter but slightly over-registers in turbulent water. The Haskell meter is less affected by floating weeds or inner bark and very slightly under-registers in turbulent water. The characteristics of these two types of meters are fully discussed by Groat and others in Trans. Am. Soc. C. E., Vol. LXXVI, 1913, pp. 819 to 870.†

To obtain good results, the current meter should receive the same care that is accorded any delicate piece of mechanism.

Rating the Meter. — In order to obtain the actual velocity of the moving water, the relation between revolutions of meter and velocity of water, through widely varying limits, must be known, that is, the meter must be rated.

The rating of the meter consists in moving it through still water, at various speeds, over a course of known length, and recording the number of revolutions made by the meter and the time consumed in traveling over the course.

The rating of the meter should be performed under as great a variety of conditions as is to be expected in the use to which the meter will be subjected. Relative to the need for uniform speed in rating, Shenehon * states:

> "It is not very important to traverse the base at a precisely uniform speed, because the stream flow which the meters measure is not entirely uniform. It comes in pulsations, sometimes lagging, sometimes spurting, and the uniformity in the rating speed need not be greater than that of the stream."

For each rate of speed the meter should be run over the course in both directions so as to eliminate any wind or current effects.

The applicability of a still-water rating to the measurement of flowing water has often been questioned. The U. S. Lake

* Shenehon, Francis C., Minnesota Engineer, Vol. 17, No. 3, p. 123.

† See also Trans. Am. Soc. C. E, Vol. LXXX, p. 1231.

Survey,* however, has proven by a series of carefully conducted experiments in 1906, that for velocities of about three feet per second, at least, the still-water rating gives absolutely correct results.

A comparison of still-water and moving-water ratings made by the U. S. Geological Survey† shows that still-water ratings are correct for all velocities above one foot per second.

TYPICAL RATING TABLE

Time in sec.	Velocity in feet per second													Time in sec.
	5 revs.	10 revs.	20 revs.	30 revs.	40 revs	50 revs	60 revs.	70 revs.	80 revs.	90 revs.	100 revs.	150 revs.	200 revs.	
40	0 31	0 58	1 13	1 68	2 23	2 78	3 34	3 90	4 45	5 01	5 56	8 34	11 12	40
41	0 30	0 57	1 10	1 64	2 18	2 71	3 26	3 81	4 34	4.89	5 43	8 14	10 85	41
42	0.30	0 56	1 07	1 60	2 13	2 65	3 18	3 72	4 24	4 77	5 30	7 95	10 59	42
43	0 29	0 54	1 05	1 56	2 08	2 59	3 11	3 63	4.14	4 66	5 18	7 77	10 34	43
44	0.28	0 53	1 03	1.53	2 03	2 53	3.04	3 55	4.04	4 55	5 06	7 59	10 10	44
45	0 28	0 52	1 01	1 50	1 99	2 48	2 97	3 47	3 95	4 45	4 95	7 42	9 87	45
46	0 28	0 51	0 99	1 47	1 95	2 43	2.90	3 39	3 87	4 35	4 84	7.26	9 65	46
47	0 27	0 50	0 97	1 44	1 91	2 38	2 84	3 32	3 79	4 26	4 74	7 11	9 45	47
48	0 26	0 49	0 95	1 41	1 87	2 33	2 78	3 25	3 71	4.17	4 64	6 96	9 25	48
49	0.26	0 48	0.93	1.38	1 83	2 28	2 72	3 18	3 63	4 09	4 54	6 81	9 06	49
50	0.26	0 47	0 91	1 35	1 79	2 23	2 67	3 12	3 56	4 01	4 45	6 67	8 89	50
51	0 25	0.46	0 90	1 32	1 75	2 19	2 62	3 06	3 49	3.93	4 36	6 54	8 72	51
52	0 25	0 46	0 88	1 29	1 72	2 15	2 57	3 00	3 42	3 85	4 28	6 42	8 56	52
53	0 24	0 45	0 86	1 27	1 69	2 11	2 52	2 94	3 36	3.78	4 20	6 30	8 40	53
54	0.24	0 44	0.85	1 25	1 66	2 07	2 47	2 88	3.30	3 71	4.12	6 18	8 24	54
55	0.24	0 43	0 83	1 23	1 63	2 03	2 43	2 83	3 24	3 64	4 05	6 07	8 09	55
56	0 23	0 43	0 82	1 21	1.60	1.99	2 39	2 78	3.18	3 58	3.98	5 96	7 95	56
57	0 23	0 42	0 80	1 19	1 57	1.96	2 35	2 73	3.12	3 52	3 91	5 86	7 81	57
58	0 22	0 41	0 79	1 17	1 54	1 93	2 31	2 68	3 07	3 46	3.84	5 76	7 68	58
59	0.22	0.41	0 78	1.15	1 51	1 90	2 27	2 63	3 02	3 40	3.77	5 66	7.55	59
60	0 22	0 40	0 77	1 13	1 48	1 87	2 23	2 59	2 97	3 34	3 71	5 56	7 42	60
61	0 22	0 39	0 75	1 11	1 46	1 84	2 19	2 55	2 92	3 29	3 65	5 47	7 30	61
62	0 21	0 39	0 74	1 09	1 44	1 81	2 16	2 51	2 87	3 24	3 59	5 38	7 18	62
63	0 21	0 38	0 73	1 07	1 42	1 78	2 13	2 47	2 82	3 19	3 53	5 30	7 07	63
64	0 21	0 38	0 72	1 05	1 40	1 75	2.10	2 43	2 77	3 14	3.48	5.22	6 96	64
65	0 20	0 37	0 71	1 03	1 38	1 72	2 07	2 39	2 73	3 09	3 43	5 14	6 85	65
66	0 20	0 37	0 70	1 02	1 36	1 69	2 04	2 35	2 69	3.04	3 38	5 06	6 75	66
67	0 20	0 36	0 69	1 01	1 34	1.66	2 01	2 32	2 65	2 99	3 33	4 98	6 65	67
68	0 20	0 36	0 68	1 00	1 32	1.64	1 98	2.29	2 61	2 95	3 28	4 91	6 55	68
69	0.19	0 35	0 67	0.99	1 30	1.62	1 95	2 26	2 57	2 91	3 23	4 84	6 45	69
70	0.19	0.35	0.66	0 98	1.28	1 60	1.92	2 23	2 53	2 87	3 18	4 77	6 36	70

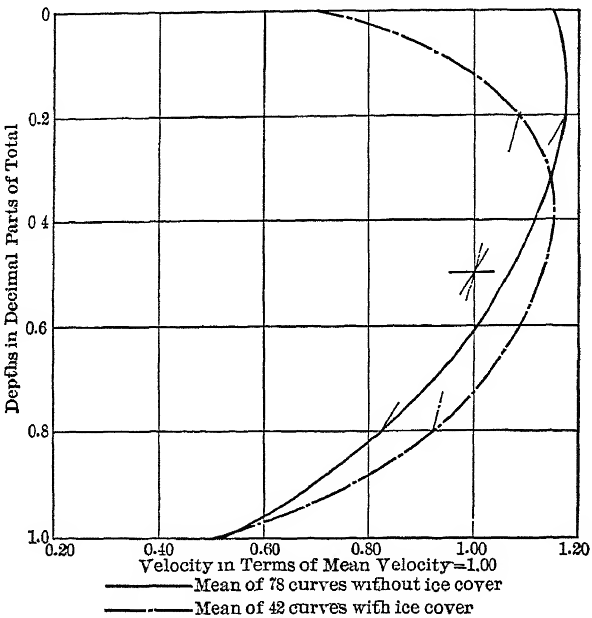
A good rating can be secured by sending the meter to the United States Bureau of Standards at Washington, which does the work for a small charge. The rating furnished by the manufacturer is usually correct to about two per cent.

* Shenehon, Francis C., Minnesota Engineer, Vol. 17, No. 3, p. 123.

† Water Supply and Irrigation Paper, No. 95.

From the rating just described, tables are prepared giving the relation between the number of revolutions of the meter in various periods of time, and the corresponding velocity of the water. A typical rating table is shown on p. 409.

The Mean Velocity. — The discharge of a stream represents the product of its cross-sectional area times its mean velocity. The area can be ascertained by soundings but the mean velocity



From U.S.G.S. Water Supply Paper No. 187.

FIG. 250. — Typical Vertical Velocity Curves with and without Ice Cover.

cannot be directly determined. It can only be computed after the discharge itself has been ascertained. This is done by summing up the partial discharges in relatively small vertical sections of the stream, determined by means of velocity measurements in the end verticals of the sections and the depths of water in these verticals, as derived from the soundings. The verticals in which velocity measurements are made may be 2, 5, 10, 20, or even 50 feet apart, depending mainly upon the width and depth of the stream and the uniformity of the flow.

Fig. 250 shows typical vertical velocity curves. A study of a large number of similar curves has resulted in establishing as a practical fact that the mean velocity in a vertical, irrespective of depth or character of stream, is found at a point approximately six-tenths of the depth below the water surface, and that the mean of the velocity at the two-tenths depth and at the eight-tenths depth will almost exactly equal the mean velocity.

The point of maximum velocity generally lies between the surface and a point at one-third of the depth. The following table shows the relation between depths of maximum and mean velocity, measured from the surface down.

Depth of point of maximum velocity	Corresponding depth of point of mean velocity
0	0.58 *d*
0 1 *d*	0 59 *d*
0 15 *d*	0.60 *d*
0 20 *d*	0.62 *d*
0 25 *d*	0.63 *d*
0 30 *d*	0.65 *d*
0.33 *d*	0.67 *d*

d = total depth of water

The usual velocity curve is a parabola with its axis horizontal through the point of maximum velocity. In such a curve the mean of the velocities at .21 and .79 of the depth below the surface theoretically gives the true mean velocity. Also, the mean of the velocities at .15, .50 and .85 depth gives the mean velocity in the vertical.*

Evidently, the use of the average of the velocities at .2 and .8 depth, for the determination of the mean velocity in the vertical, is correct in theory, and it is also fully substantiated by a great many observations.

When a high degree of accuracy is required in meter gaging, two meters may be used to advantage. One is held continually at the .6 depth while the other is held successively at .2

* Engineering News, Vol. 75, p. 889.

and .8 depth, or at each tenth depth in case vertical curves are to be plotted. The meter which measures the mean velocity directly at the .6 depth can be used to indicate changes in velocity due to the pulsations noticeable in the flow of nearly all streams. In shallow, turbulent, and hence rough-bedded streams, the measurements of velocity at .6 depth usually gives results that are less in error than when measurements at .2 and .8 depth are attempted.

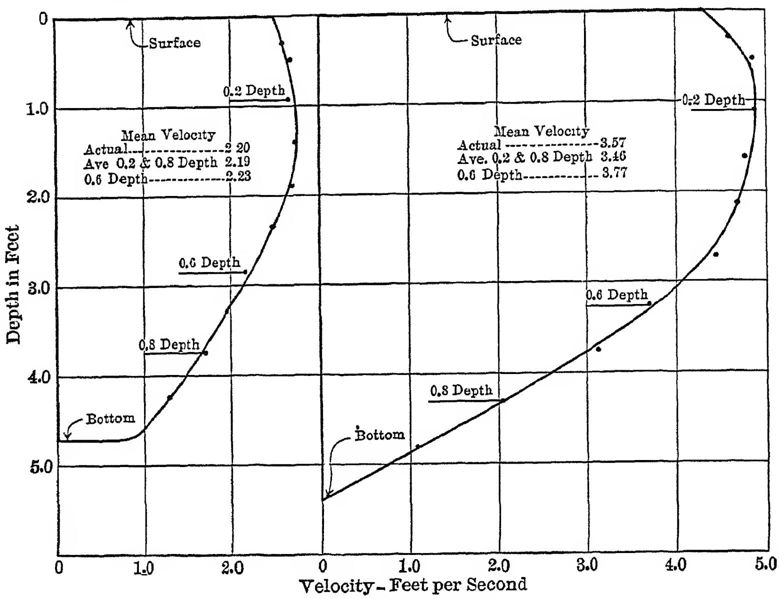


FIG. 251.—Typical Vertical Velocity Curves in Tailrace of Power Plant.

In extremely swift water it may be impracticable to sink the meter far below the surface. Under such conditions measurements of velocity may be made at about half a foot below the surface and 85 per cent of these values taken as the approximate mean velocity in the vertical.

In measuring velocity it is also possible to obtain the mean in the vertical by what is known as the integration method, *i.e.*, by moving the meter through the entire depth at a uniform speed. The Price meter is not adapted for use with this method.

The Haskell meter gives correct results, as vertical motion has no effect on the wheel.

In measuring the discharge through sluice gates and from turbines it is usually necessary to determine the velocity for each tenth of depth in the vertical, as the point of mean velocity does not always have its usual location on account of initial impulses received by the water. Typical vertical curves taken by the author in connection with power plant tests are shown in Fig. 251.

Making the Measurement. — When the meter section is located at a bridge, the meter may be held over the edge of the roadway or the railing, or suspended from the end of a spar so as to get the meter beyond the influence of the piers. When meterings are made from a boat, the boat is kept in position by means of a wire or cable stretched across the stream, or by means of an anchor. When a cable is used, it may be marked to serve also as a tag line; and when the river must be kept open for boats or floating logs, the cable may be permitted to rest on the bottom except at the measuring point. When the use of a cable is impracticable, the position of the measuring point on the cross section may be determined by sextant, as previously indicated.

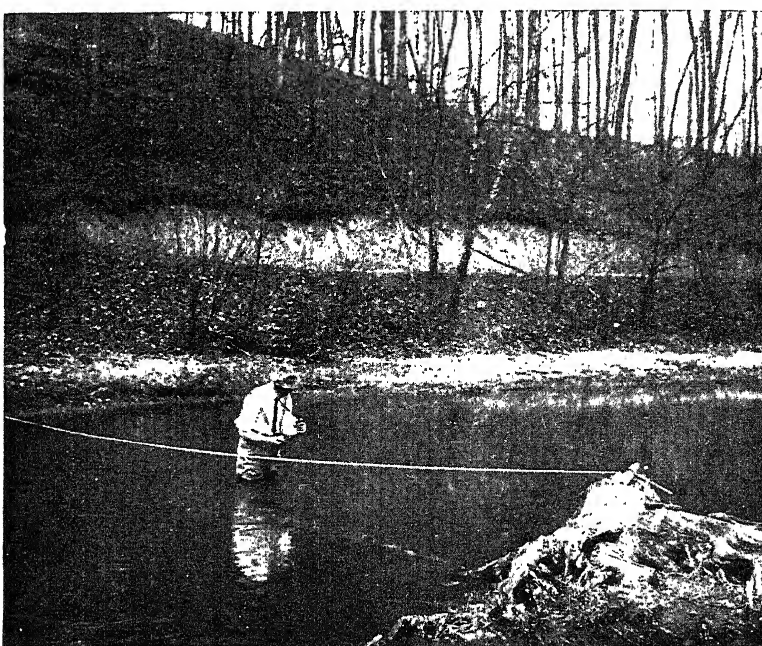
On the smaller streams a cable and car can advantageously be used for making the measurement. Typical U. S. Geological Survey metering stations are shown in Figs. 252 to 255.

The meter is held in position and the number of revolutions observed for from 40 to 70 seconds, at each .2 and .8 depth on each vertical, consecutively, across the stream. These verticals, as previously stated, may be from 2 to 50 feet apart, depending upon the character of the channel. The gage at both the gaging station and at the meter section — if these are not at the same place — should be read at the beginning and at the end of the metering to indicate changes in stage.

The meter may be suspended from a cable with the aid of a weight or, in measuring small streams, it may be attached

From U.S.G.S. Water Supply Paper No. 94.

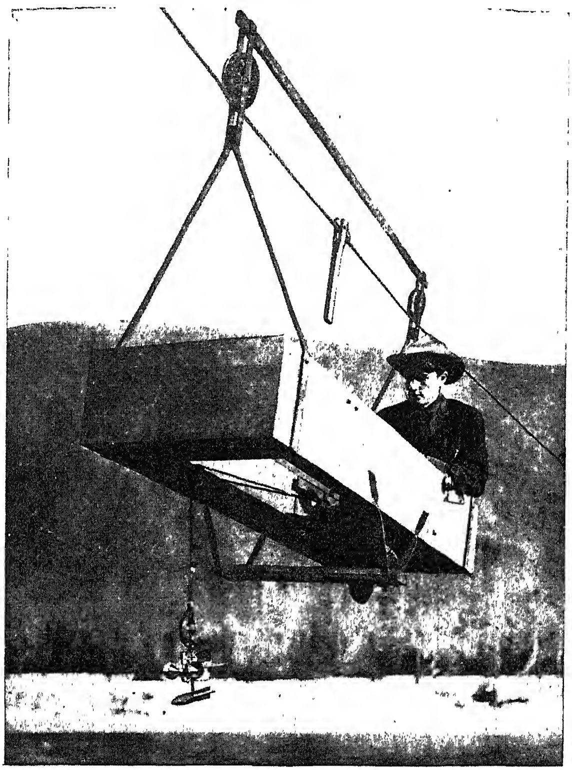
FIG. 252.—Making a Meter Measurement from a Boat.



From U.S.G.S. Water Supply Paper No. 304.

FIG. 253.—Making a Wading Measurement.

to the end of a rod. In deep, swift water a guy line may be necessary to keep the meter in the vertical; or the pull and angle of the cable at the observer's end may be recorded and the proper position of the meter computed.

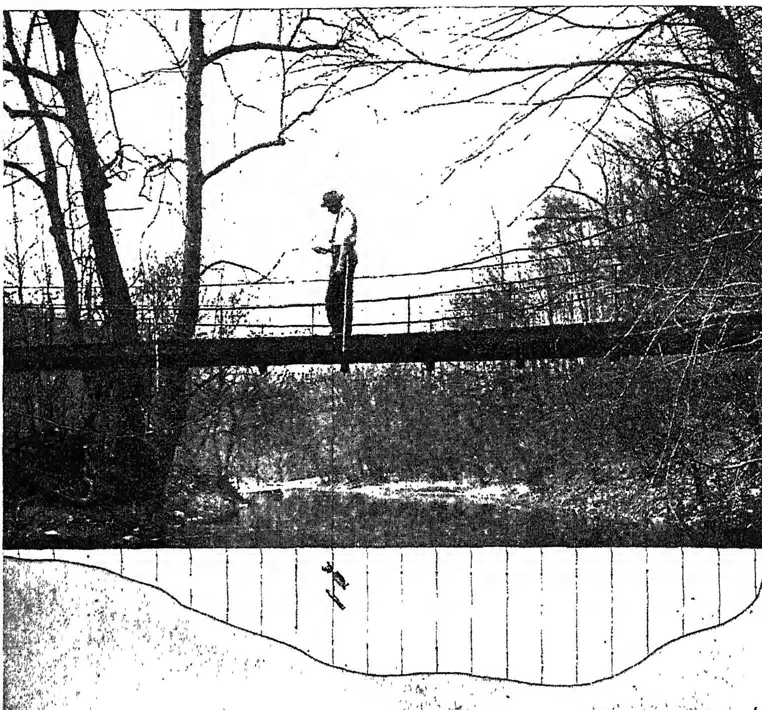


From U.S.G.S. Water Supply Paper No. 371.

Fig. 254.—Making a Meter Measurement from a Cable Car.

In deep, swift water the meter may also be suspended from a piece of uninsulated piano wire or small cable and the circuit completed by dropping the observer's end of the wire, having a metal plate attached, into the water. This arrangement offers very little resistance to the flow of water and consequently keeps the meter in a very nearly vertical position.

The most common devices for determining the revolutions of the meter in a given time are the electrical register and the telephone receiver. The latter is light, which is of importance in wading measurements, but focuses the attention of the observer on the counting of the clicks of either single, fifth or



From U.S.G.S. Water Supply Paper No. 304.

FIG. 255. — Making a Meter Measurement from a Bridge.

tenth revolutions, according to the device used in the meter. The electrical register is automatic and requires merely the starting and stopping of the mechanism and the reading of the number of revolutions and the time. A stop-watch is essential in accurate work.

The Field and Office Notes. — Whenever a considerable amount of meter gaging is to be done, special notebooks or

loose-leaf blanks with proper printed column headings should be prepared and used in recording the field observations and also the results of the necessary office computations. Any unusual circumstances surrounding the measurement should also be recorded in the notes for possible future use in the interpretation of irregularities in the observations.

Two typical sheets from a set of field notes of a meter measurement are shown on the following pages.

The Discharge Curve. — After meter measurements have been made through at least the principal range in stage on the given stream, a " discharge curve " (Fig. 256) is drawn on cross-section paper by plotting the metered discharges against the corresponding observed gage heights. With the smoothed curve drawn through the observed points as a basis, a table is prepared for office use, giving the discharge in cubic feet per second corresponding to each tenth or half tenth foot in gage height. Such a table for the Ottertail River is shown below.

If possible, a field determination should be made of the gage height corresponding to zero flow. If the gaging station is located above a well-defined point of control, zero flow will correspond to the gage height that represents the elevation of the river bottom at the control. This can usually be determined by soundings at the time the gaging station is established. The gage height corresponding to the stage of zero flow helps greatly in determining the low-water portion of the discharge curve.

If the gaging station is established at a good point of control, and the discharge curve has once been well determined, a single metering a year, taken at the time the zero of the gage is checked, will usually give sufficient verification of the curve and hence of the stability of the control.

In case the meter section is not at the gaging station the cross section of the stream at the gage should also be determined so that both area and mean velocity curves at the gage may

TYPICAL DISCHARGE MEASUREMENT NOTES

Date......July 21.........., 1916. No. of Meas....................

....Ottertail................ River at GermanChurch State of..Minn......
~~Creek~~ near Fergus Falls

Width.....65.........Area.....218.....Mean Vel....3.27..... Cor. M. G. H. 2.58

Party.....S. B. Soule'........................ .... Disch. 713 c.f.s.

Staff gage, checked with ~~level~~ and found..

Chain length, checked with steel tape, 12-lb. pull, found......16.26..........ft.

" " not changed ~~to............ ft. at.............o'clock.~~ Correct length.....16.26......ft.

" " corrected on basis of levels to........................ft. at........................o'clock.

Gage reading	Time	Station
2.58	6 00 P.M.	Before
2.58	7 25 P.M.	After

Weighted mean G. Ht. ......2.58........ft.

Correct " " " ......2.58........ft.

Meter No...911 S.P...........................

Date rated...Nov. 24 1915.............

Meas. began 6 00 P.M.; ended 7 25 P.M..

Time of meas. (hrs) 1 25/60...Method. 2 Pt.

No. meas. sec's...34.....Coef..1.00.......

Av. width sec. ..1.9.......Av. depth..3.4...

G. Ht. change (total.) .....:00................

....+3...% diff. by...11/20/15...rating table.

Meas. from ~~cable~~, bridge, ~~boat, wading.~~ Meas. at.......................... ~~ft. above, below~~ gage.

If not at regular section note location and conditions..

....Area from soundings (date) This meas....

Method of suspension Small sash cord Stay wire...............Approx. dist. to W. S. ....10.....

Arrangement of weights and meter; top hole.........; middle hole..M....; bottom hole..15#..

Gage inspected, found.......O.K................ Cable inspected, found...........................

Distance apart of measuring points verified with steel tape and found...............................

Wind.....None..... ~~upstr., downstr., across.~~ Angle of current ......Normal............

Observer seen........No............... G. Ht. book inspected.......No...........................

Examine station locality and report any abnormal conditions which might change relation of G. Ht. to disch., e. g., change of control; ice or debris on control; backwater from; condition of station equipment............Control clear...

....

Sheet No. 1 of....6......sheets. If insufficient space, use back of sheet, with reference letters.

July, 1914

TYPICAL DISCHARGE MEASUREMENT NOTES

Date July 21 1916 No. of Meas.

Ottertail River, at German Church

Dist. from initial point	Depth	Depth of observat.	Rev-olu-tions	Time in sec-onds	VELOCITY At point	Mean in ver-tical	Mean in sec-tion	Area	Mean Depth	Width	Discharge
28	3.9	.8	70	40	3.95	3.68					
		3.1	60	40	3.40		3.68	7.8	3.9	2	28.7
30	3.9	.8	70	39½	4.00	3.68					
		3.1	60	40½	3.36		3.68	7.7	3.85	2	28.3
32	3.8	.8	70	40	3.95	3.68					
		3.0	60	40	3.40		3.73	7.6	3.8	2	28.3
34	3.8	.8	70	40	3.95	3.78					
		3.0	70	44	3.60		3.73	8.1	4.05	2	30.2
36	4.3	.9	70	40	3.95	3.68					
		3.4	60	40	3.40		3.26	8.8	4.4	2	28.7
38	4.5	.9	70	42½	3.72	2.85					
		3.6	40	46	1.98		2.64	9.0	4.5	2	23.8
40	4.5	.9	70	43½	3.64	2.44					
		3.6	30	56	1.23		2.68	9.0	4.5	2	24.1
42	4.5	.9	70	44	3.60	2.93					
		3.6	40	40	2.26		2.94	8.6	4.3	2	25.3
44	4.1	.8	60	39	3.48	2.94					
		3.3	50	47	2.41		3.04	8.0	4.0	2	24.3
46	3.9	.8	60	40	3.40	3.15					
		3.1	50	39	2.90		3.18	7.4	3.7	2	23.5
48	3.5	.7	70	45	3.52	3.22					
		2.8	60	46½	2.92		3.15	6.6	3.3	2	20.8
50	3.1	.6	70	43½	3.64	3.08					
		2.5	50	45	2.51		3.24	6.1	3.05	2	19.8
Totals								94.7			305.8

No. 3 of 6 Sheets. Comp. by S. B. S. Chk. by S. B. S.

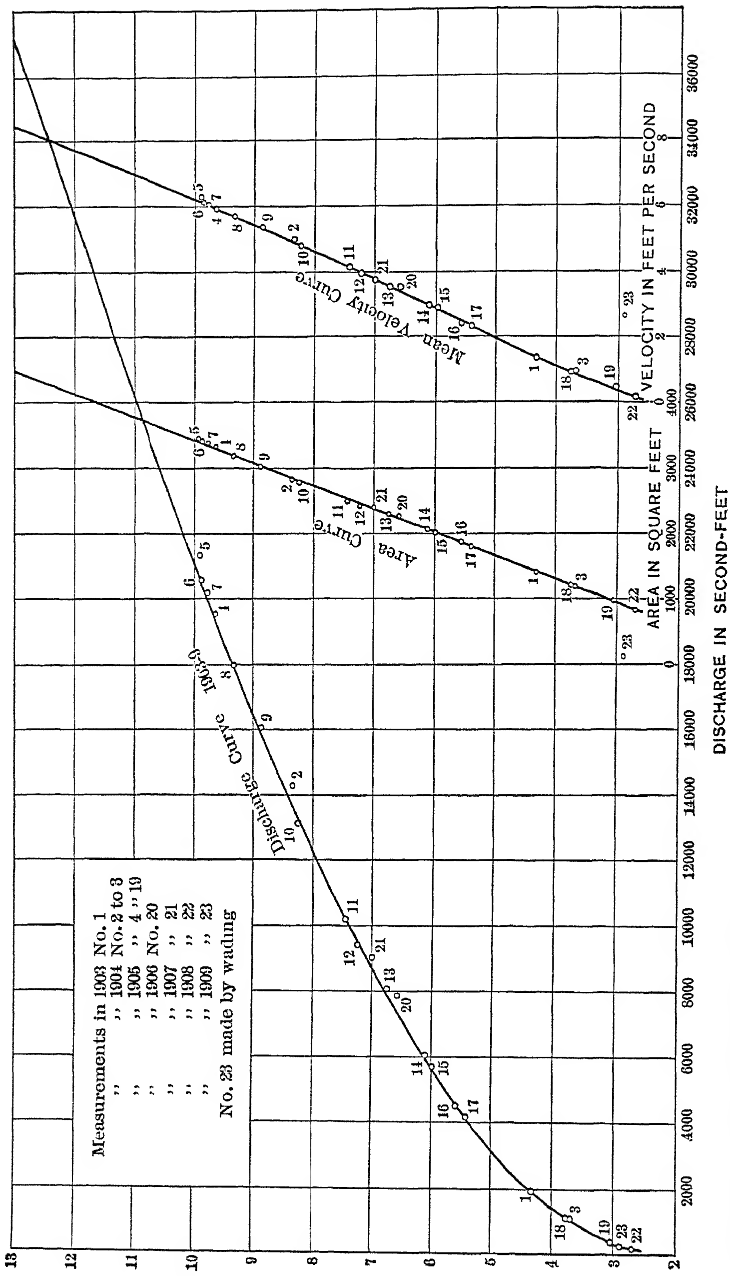


Fig. 256.—Typical Discharge Curve.

From U.S.G.S. Water Supply Paper No. 263.

be plotted in addition to the discharge curve. The mean velocity is determined by dividing the measured discharge by the cross-sectional area of the stream *at the gaging station*, and not at the meter section, in case the two are not identical.

TYPICAL DISCHARGE TABLE

Ottertail River (at German Church) near Fergus Falls, Minn.
October 29, 1913 to September 30, 1916

Gage height, feet	Discharge, c.f.s.	Difference, c.f.s.	Gage height, feet	Discharge, c.f.s.	Difference, c.f.s.	Gage height, feet	Discharge, c.f.s.	Difference, c.f.s.	Gage height, feet	Discharge, c.f.s.	Difference, c.f.s.
1.00	140										
		18			24			42			62
1.10	158		1.60	261		2.10	434		2.60	704	
		19			27			46			65
1.20	177		1.70	288		2.20	480		2.70	769	
		19			31			50			68
1.30	196		1.80	319		2.30	530		2.80	837	
		20			35			54			71
1.40	216		1.90	354		2.40	584		2.90	908	
		21			38			58			74
1.50	237		2.00	392		2.50	642		3.00	982	
		24			42			62			

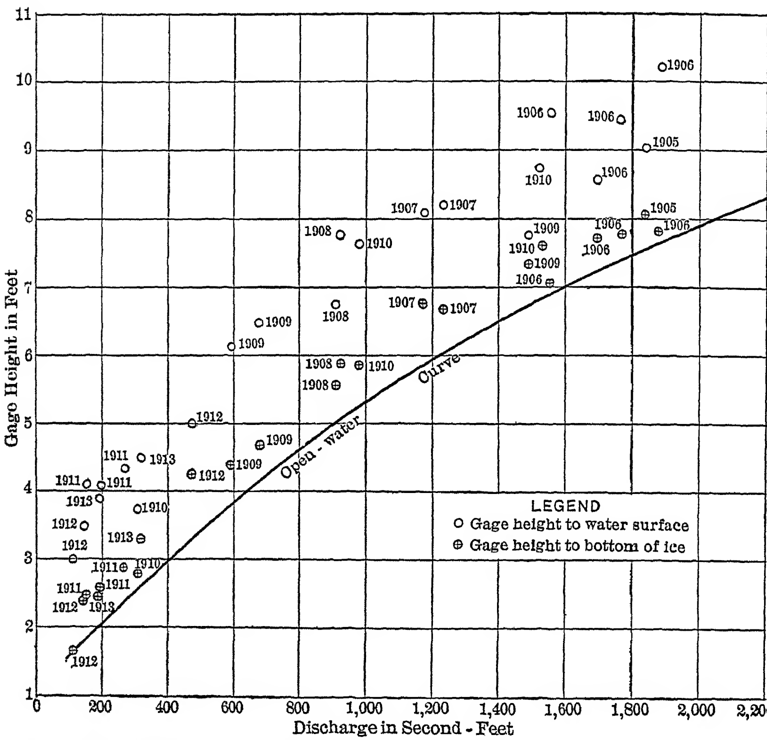
The above table is not applicable to ice or obstructed channel conditions. It is based on nine discharge measurements made during 1913, 1914, 1915, and 1916 and is well defined between 237 c.f.s. and 837 c.f.s.

The curve of mean velocity will indicate the effect of changes in stage if the gage is located a considerable distance above the control. The nearer the gage is to the control, the less the effect of change in stage. On a rising stage the slope of a stream between successive points of control is greater, and hence the velocity greater, at the same stage, than on a falling stage.

If, through floods, the control at the gage is changed, a new discharge curve must be prepared. If the channel is so unstable as to be continually shifting, frequent discharge measurements are imperative, and the determination of the daily discharge becomes a relatively difficult matter.*

* This phase of the subject is fully discussed by Hoyt & Grover in their "River Discharge" and in Water Supply Paper, No. 371, p. 117; and No. 345, p. 53.

Effect of Ice on Discharge. — The friction due to ice cover is very much greater than that due to air; consequently, a given amount of water, flowing in an open channel, can only be carried in an ice-covered channel on an increased slope or through an increased area of cross section. The result is a higher stage, under ice cover, for the same discharge.



From U.S.G.S. Water Supply Paper No. 337.

FIG. 257. — Relation between Open-Water Curve and Ice Measurements, Red River at Grand Forks, Minn.

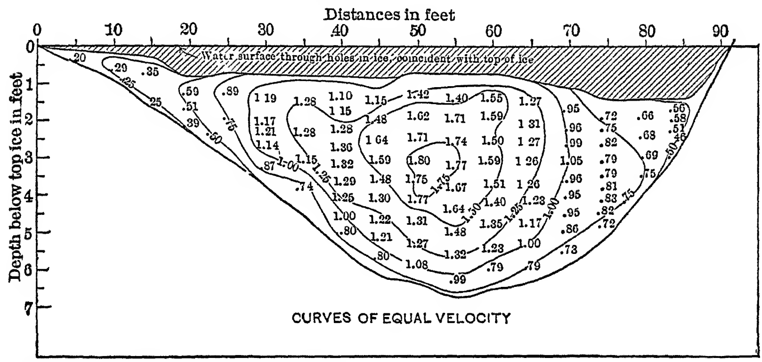
The increased frictional resistance due to ice cover is well shown by the shape of the vertical velocity curve in Fig. 250 and the location of the winter discharge measurements with respect to the discharge curve of Fig. 257.

When the control remains open all winter, and free from anchor ice, the daily discharge may be determined from the

observed gage heights and the open-water discharge curve. When ice forms over the control, however, no constant relationship exists between gage heights and discharge.

The best results appear to be obtained from frequent meter measurements combined with a study of the temperature and its effect on the regimen of the stream.*

Under ice conditions, velocity measurements are made at .2 and .8 depth, measured from the bottom of the ice. Gage heights are determined by chopping the ice away around the gage and reading the height of the water itself. Usually weekly readings are sufficient during the frozen season.



From U.S.G.S. Water Supply Paper No. 337.

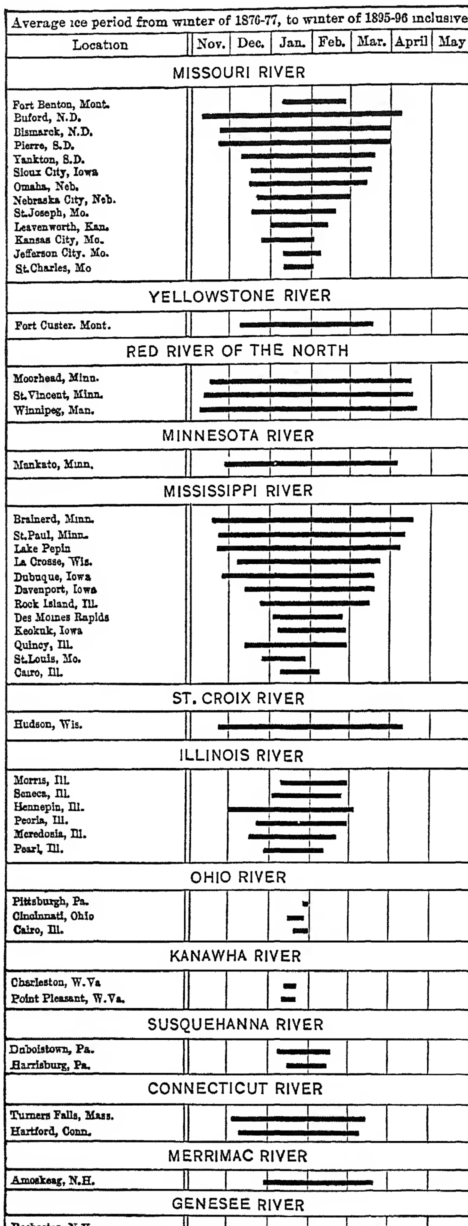
FIG. 258. — Curves of Equal Velocity in Ice-Covered Channel Cannon River at Welch, Minnesota.

Fig. 258 shows curves of equal velocity of water in an ice-covered channel, and Fig. 259 shows the average duration of the ice period on the principal rivers of the United States.

Other Methods of Measuring Stream Flow

Float Measurements. — Floats were generally used in hydrometric work until 1880. Since then, they have been gradually displaced by current meters. At present, floats are seldom used except under unusual conditions, such as at time of flood or in connection with reconnaissance work.

* See U. S. G. S. Water Supply Paper, No. 337, "The Effects of Ice on the Flow of Streams" by W. G. Hoyt, 1911; also No. 187 by Barrows & Horton.



From Report of U. S. Deep Waterways Commission.

FIG. 259.—Average Duration of Ice Period.

Floats may be classed as surface, subsurface, and rod floats. Surface floats consist of light objects, such as wood or corked bottles, whose velocity when floating on the surface of the water is measured directly by observing the time required to pass a given distance. The mean velocity in the vertical will be about 85 per cent of the surface velocity.

Subsurface floats consist of a relatively large submerged object attached, by means of a line, to a light marker floating on the surface. The subsurface float can be arranged to float at any depth, and hence will give an approximate value for mean velocity directly. This type of float was used by Humphreys and Abbot in gaging the Mississippi River in 1851 and 1858.*

In general, subsurface floats give better results than surface floats but are less accurate than rod floats.

Tube or rod floats consist of a tin tube or a wooden rod from one to three inches in diameter, of such a length and so weighted as to float at a depth as nearly equal to the full depth of the channel as possible. Rod floats are best adapted to regular or artificial channels. The mean velocity is computed by the Francis formula:

$$Vm = Vr\left\{1.000 - 0.116\left(\sqrt{D} - 0.1\right)\right\},$$

in which

Vm = mean velocity in vertical;
Vr = observed rod float velocity;
D = proportion of depth not reached by rod.

Considerable precision has been secured in making rod float measurements of the Mississippi River at St. Louis since 1900.† In April, 1912, gagings were made at observed rod velocities ranging from 7 to 12 feet per second, and a gage height of 30.7 feet. Floats up to 46 feet long were used. The width of the stream at the gaging station was about half a mile.

* Report upon the Physics and Hydraulics of the Mississippi River by Humphreys and Abbot, 1861, p. 224.

† Mississippi River Gagings by Rod Floats by Frederick Y. Parker; Professional Memoirs, U. S. Corps of Engineers, Vol. V, p. 724.

In making float measurements a range about 200 feet in length is selected on a portion of the channel that is as straight and uniform in depth and cross section as possible. The velocity is measured at from five to twenty or more float stations, spaced as nearly equidistant across the channel as possible. Every float course is carefully sounded, and from the mean velocities and areas of the subdivisions of the cross section of the stream, partial discharges are computed and from these the total discharge of the stream is secured. The detailed method to be adopted in any particular case will be dependent, mainly, upon the characteristics of the channel whose discharge is to be determined. One of the principal objections to float measurements is the amount of labor and floating equipment required on the work. Under favorable conditions, however, and when the work is carefully done, a high degree of accuracy can be secured.

Slope Measurements. — The velocity of flowing water depends upon the slope and character of its channel. As the friction on the bed of the stream and against its banks becomes relatively less effective, with increasing depth, the velocity is also indirectly dependent upon the mean depth. Chezy in 1775 expressed these relations in the following formula:

$$v = c\sqrt{rs},$$

in which

v = mean velocity in feet per second;
c = a coefficient depending mainly upon the character of the channel and varying from about 25 to 200;
r = the hydraulic radius, or area of cross section in square feet divided by the wetted perimeter in feet. (In natural channels this is approximately equal to the area divided by the width plus the mean depth.)
s = the slope, or feet fall per foot. (To be determined by leveling.)

The coefficient c may be calculated by Kutter's formula:*

$$c = \frac{41.6 + \frac{.00281}{s} + \frac{1.811}{n}}{1 + \left\{41.6 + \frac{.00281}{s}\right\} \frac{n}{\sqrt{r}}}.$$

It has been found by repeated measurement that, for the same channel conditions, the coefficient n in the Kutter formula decreases with increase in depth. This appears to be due, in part at least, to the lesser effect, at high stages, of eddies due to irregularities in the channel bed.

Simple diagrams for the solution of Kutter's formula are those given by Kennison in Engineering News, June 20, 1912, p. 1191; and by Fish in Engineering News, April 15, 1915, p. 733.

Another formula frequently used in the determination of the coefficient c is the Bazin formula:

$$c = \frac{87}{.552 + \frac{m}{\sqrt{r}}}.$$

Hillberg † found that a simple relation exists between the coefficients used by Bazin and by Kutter. He expressed this relation by the equation: $m = 87\,n - 1$.

The best values of n for use in Kutter's formula are those given by Horton ‡ in the following table. The equivalent values of m in Bazin's formula have been computed by means of Hillberg's formula and added for use in determining c.

Whenever the slope of a channel is greater than 1.5 feet per mile, the slope term in Kutter's formula has relatively little effect on the value of c. This fact is shown in Fig. 260. The relation between r and c is shown in Fig. 261. When $r = 3.28$ feet the value of c is independent of the slope and its value is $\frac{1.811}{n}$. The effect of variations in n on the value of c is shown in Fig. 262.

* Ganguillet & Kutter, The Flow of Water in Rivers and other Channels.

† Hillberg, A. G., Engineering Record, Oct. 21, 1916, p. 494.

‡ Horton, Robert E., Engineering News, Feb. 24, 1916, p. 373.

TABLE 41. — NEW TABLE OF n FOR KUTTER'S FORMULA (Horton) AND CORRESPONDING VALUES OF m FOR BAZIN'S FORMULA

Surface	Perfect		Good		Fair		Bad	
	n	m	n	m	n	m	n	m
Uncoated c.-i. pipe	0 012	0 044	0 013	0 131	0 014	0 218	0 015	0 305
Coated c.-i. pipe	0 011	−0 043	0 012*	0 044	0 013*	0 131		..
Commercial w.-i. pipe, black	0 012	0 044	0.013	0 131	0 014	0 218	0 015	0 305
Commercial w.-i. pipe, galv.	0 013	0 131	0 014	0 218	0 015	0 305	0 017	0 479
Smooth brass and glass pipe	0 009	−0 217	0 010	−0 130	0 011	−0 043	0 013	0 131
Smooth lockbar and welded "OD" pipe	0.010	−0 130	0 011*	−0 043	0 013*	0 131	....	....
Riveted and spiral steel pipe	0.013	0 131	0 015*	0 305	0 017*	0 479	....	....
Vitrified sewer pipe	0 010 0 011	−0 130 −0 043	0 013*	0 131	0 015	0 305	0 017	0 479
Glazed brickwork	0 011	−0.043	0 012	0 044	0 013*	0 131	0 015	0 305
Brick in cement mortar; brick sewers	0 012	0 044	0 013	0 131	0 015*	0.305	0 017	0 479
Neat cement surfaces	0 010	−0 130	0.011	−0 043	0 012	0 044	0 013	0 131
Cement mortar surfaces	0 011	−0 043	0 012	0 044	0 013*	0 131	0 015	0 305
Concrete pipe	0.012	0 044	0 013	0.131	0 015	0 305	0 016	0 392
Wood-stave pipe	0 010	−0 130	0 011	−0.043	0.012	0 044	0 013	0 131
Plank flumes:								
Planed	0.010	−0 130	0 012*	0 044	0 013	0 131	0 014	0 218
Unplaned	0 011	−0 043	0 013*	0 131	0 014	0 218	0 015	0.305
With battens	0 012	0 044	0 015*	0 305	0 016	0 392		
Concrete-lined channels	0 012	0 044	0 014*	0 218	0 016*	0.392	0 018	0 566
Cement-rubble surface	0.017	0.479	0.020	0 740	0 025	1.175	0 030	1 61
Dry-rubble surface	0 025	1.175	0 030	1.61	0 033	1 87	0 035	2 04
Dressed-ashlar surface	0 013	0 131	0.014	0 218	0 015	0 305	0 017	0 479
Semicircular metal flumes, smooth	0.011	−0 043	0.012	0 044	0 013	0 131	0 015	0 305
Semicircular metal flumes, corrugated	0.0225	0.958	0 025	1.175	0 0275	1 39	0 030	1 61

* Values commonly used in designing.

TABLE 41. — NEW TABLE OF n FOR KUTTER'S FORMULA (Horton) AND CORRESPONDING VALUES OF m FOR BAZIN'S FORMULA — (*Continued*)

Surface	Perfect		Good		Fair		Bad	
	n	m	n	m	n	m	n	m
Canals and ditches:								
Earth, straight and uniform	0.017	0.479	0.020	0 740	0 0225*	0 958	0 025	1 175
Rock cuts, smooth and uniform	0.025	1.175	0.030	1.61	0 033*	1 87	0 035	2.04
Rock cuts, jagged and irregular	0.035	2.04	0 040	2.48	0 045	2.92	. .	
Winding sluggish canals	0.0225	0.958	0 025*	1 175	0 0275	1 39	0 030	1 61
Dredged earth channels	0 025	1.175	0 0275*	1 39	0.030	1 61	0.033	1 87
Canals with rough stony beds, weeds on earth banks	0.025	1.175	0 030	1 61	0 035*	2 04	0 040	2 48
Earth bottom, rubble sides	0.028	1.44	0.030*	1.61	0 033*	1.87	0.035	2 04
Natural stream channels:								
(1) Clean, straight bank, full stage, no rifts or deep pools	0.025	1.175	0.0275	1.39	0.030	1.61	0 033	1 87
(2) Same as (1), but some weeds and stones	0.030	1.61	0.033	1 87	0 035	2.04	0 040	2 48
(3) Winding, some pools and shoals, clean	0 033	1.87	0.035	2.04	0.040	2.48	0 045	2 92
(4) Same as (3), lower stages, more ineffective slope and sections	0 040	2.48	0 045	2 92	0 050	3.35	0 055	3 78
(5) Same as (3), some weeds and stones	0 035	2 04	0 040	2 48	0 045	2 92	0 050	3 35
(6) Same as (4), stony sections	0 045	2.92	0 050	3 35	0 055	3 78	0.060	4 22
(7) Sluggish river reaches rather weedy or with very deep pools	0 050	3.35	0.060	4 22	0 070	5 09	0 080	5 96
(8) Very weedy reaches	0.075	5 52	0.100	7.70	0.125	9.88	0 150	12 05

* Values commonly used in designing.

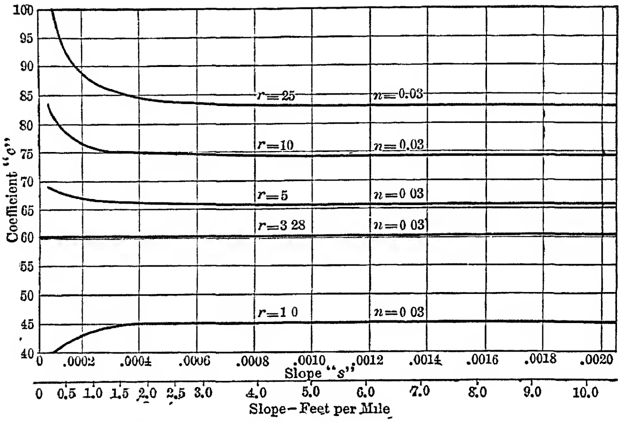


FIG. 260.—Effect of Slope of Channel on Value of Coefficient c.

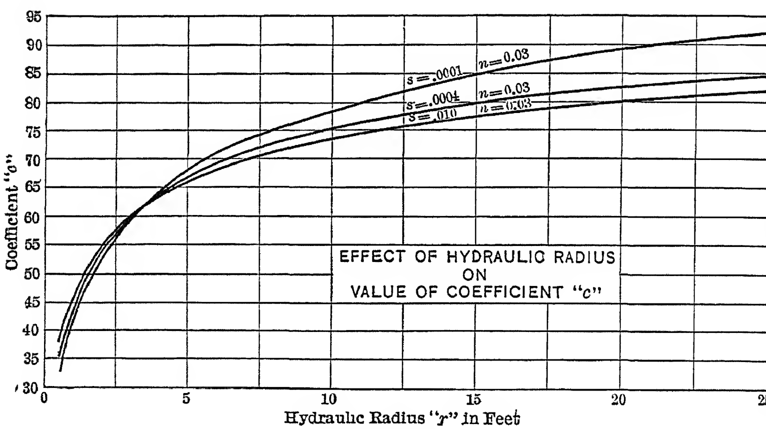


FIG. 261.

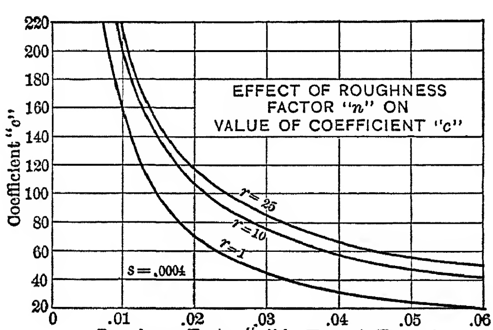


FIG. 262.

Changes in temperature have a very appreciable effect on the flow of water. Butcher * has reduced the experimental results of Mair and Saph and Schoder to the uniform basis of a velocity of 6 feet per second with the following results:

Experiments by Mair		Experiments by Saph and Schoder	
Temp. deg. F.	Values of c.	Temp. deg. F.	Values of c.
57	117	40	108
70	120	55	112
80	121	70	116
90	123	....	... .
100	125	....	.. ..
110	127	....	.. ..
120	129	....	.. ..
130	130	....	. . ..
160	136	.. ..	. . . .

The determination of the flow of streams from measurements of the slope of the water surface and the cross-sectional area finds its principal application in connection with flood discharges, backwater due to dams and similar obstructions, and the discharge capacity of artificial or improved natural channels.

In backwater computations the coefficient c or n can be determined directly by measurement in the upper and critical reaches of the stream. In computing the increased discharge capacity of channels under improvement similar determinations of c will be of great assistance. Where the channel depths vary greatly as in cases of overflow, the cross section should be subdivided and different values of c used for the different portions of the section.

The Chemical Method. — The principle involved in the measurement of the flow of water through turbines, in canals, or in natural channels, by the use of chemicals, is very simple. If S pounds of chemical are added, each second, to a stream discharging Q cubic feet of water per second, and if, after the chemical has become uniformly distributed through the

* Butcher, W. E., Engineering News, 1916, Vol. LXXVI, p. 326.

water, a sample of the dosed water tests 1 pound of chemical in W pounds of water, then:

$$\frac{S}{62.5\,Q} = \frac{1}{W}; \quad \text{or} \quad Q = \frac{WS}{62.5}.$$

The chemicals most commonly used are sodium chloride (common salt) and calcium chloride. Sulphuric acid, caustic soda and bicarbonate of soda have also been used. The best chemical for each particular instance usually depends, mainly, upon the chemical constituents of the water to be tested. When the ratio of dilution is to be determined by the color of the water, an aniline dye is used.

Although the principle involved in chemical measurements of the flow of water is simple, yet extensive refinements are necessary in its practicable application, if a high degree of accuracy is to be attained. The principal difficulties involved in this method lie in securing uniform composition in the dosing solution and a thorough mixture of the solution with the water before the sample from which the ratio of dilution is to be determined is taken.

In order to secure an accuracy of less than one per cent, it is necessary to use a quantity of salt solution which will give a ratio of weight of salt to weight of dosed water of at least one part in 75,000 to 25,000 according to the method used in testing for the salt.

Perhaps the best method of determining the ratio of dilution when the water is dosed with sodium chloride is by titrating for the chlorine by the use of silver nitrate and potassium chromate. The addition of silver nitrate to the salt solution precipitates the white silver chloride. By keeping the proper amount of potassium chromate indicator in the solution, the first drop of silver nitrate in excess of that required to precipitate all of the sodium chloride will change the color of the solution to orange. Knowing the degree of concentration of the silver nitrate solution and the amount used in precipitating all of the sodium chloride in the given quantity of water, the

ratio of dilution becomes known. As a matter of convenience, the concentration of the silver nitrate solution may be so adjusted that the volume of this solution consumed in precipitating the sodium chloride is numerically equal to the weight of the salt in the volume of water tested. One gram of silver nitrate will precipitate .344 gram of salt.

A dosing solution of 300 grams of sodium chloride per liter of water is a satisfactory strength to use. When large quantities of water are to be measured, the ratio of dilution adopted for the purpose of limiting the amount of dosing solution required may be so great as to necessitate the evaporation of some of the water from the sample so as to give a degree of concentration which will admit of sufficiently accurate determinations of the amount of dosing chemical present in the sample taken for test. A half liter of dosed water is a satisfactory size of sample to use. This may be evaporated to about 10 c.c. for titration.

The accuracy of titration is dependent upon the amount of silver nitrate used in precipitating the chlorine. As the burette used for dropping the silver nitrate into the sample can readily be read to about .1 c.c., a titration which requires 40 c.c. of silver nitrate will give an accuracy of well within one quarter of one per cent.

It has been shown by Mellet * and Groat, † in actual tests, that silver nitrate titrations for chlorine can be made with an accuracy of one tenth of one per cent.

One and one half grams of silver nitrate per liter of distilled water for the silver solution and 50 grams of potassium chromate per liter for the indicator are satisfactory concentrations to use for these solutions.

The silver nitrate solution may be made up at ten times

* Mellet, R., Bul. Technique de la Suisse, Romande, Nr. 11, 10 Juin, 1910, Lausanne.

† Groat, Benj. F., Chemi-Hydrometry and its Application to the Precise Testing of Hydro-electric Generators, Proc. Am. Soc. C. E., Vol. XLI, Nov., 1915, p. 2103.

the required strength and kept away from the light. A small amount is then taken and properly diluted for use in titrations. About one drop of potassium chromate indicator is required for each 10 c.c. of silver nitrate used in precipitating the chlorine. Groat found that 30 to 40 inversions of the bottle are required to secure a good mixture of chemicals when making titrations.

In measuring the flow of water, titrations for chlorine should be made of samples of the normal untreated water in the stream, of the dosing solution used, and of the salted water after the dosing solution has become thoroughly mixed with the water. The methods to be applied in dosing and sampling the water are dependent, primarily, upon the character of the stream to be measured, whether a mountain torrent, a brook, a large sluggish stream, a canal, or a tailrace.

In canals and headraces, the dosing solution may be forced into the water through $\frac{1}{8}$- to $\frac{1}{4}$-inch openings in several lines of horizontal pipes, under considerable pressure, which may be maintained by a 6- or 8-inch centrifugal pump into whose suction pipe the dosing solution is drawn through a smaller pipe. Samples of the dosed water are drawn up through perforated pipes each having its individual pump.

Groat found in testing power plants, that 5 or 6 minutes were required after starting to dose the water in the headrace, before conditions of flow in the tailrace had become steady. He also found that about 15 minutes were required for a satisfactory run.

A discussion of all the refinements required to secure accurate results is beyond the scope of this treatise. A full discussion of the chemical method of measuring the flow of water will be found in the papers of B. F. Groat, in Proc. Am. Soc. C. E., November, 1915, pages 2103 to 2427, and Proc. Eng'r Soc. of Western Penn., May, 1914, Vol. 30, page 374, from which the above comments have been largely drawn.

Diaphragm or Traveling Screen.—Where an extremely uniform cross section of channel is available, such as a concrete or timber-

lined canal, very accurate measurements of mean velocity can be made by observing the rate of travel of a vertical diaphragm or "screen" made of light material and accurately fitted to the cross section of the channel. By recording the velocity over a measured base 50 to 100 feet in length, by means of electrical contacts at each end, a record of the mean velocity of the flowing water is secured directly. The only correction required is for leakage around the edges of the screen. This depends principally upon the closeness of the fit and the force required to move the screen. Usually this correction is small as the necessary clearance at the edges of the screen may be reduced to about one half inch or less, and the velocity of the water at the extreme sides of the channel is less than the mean.

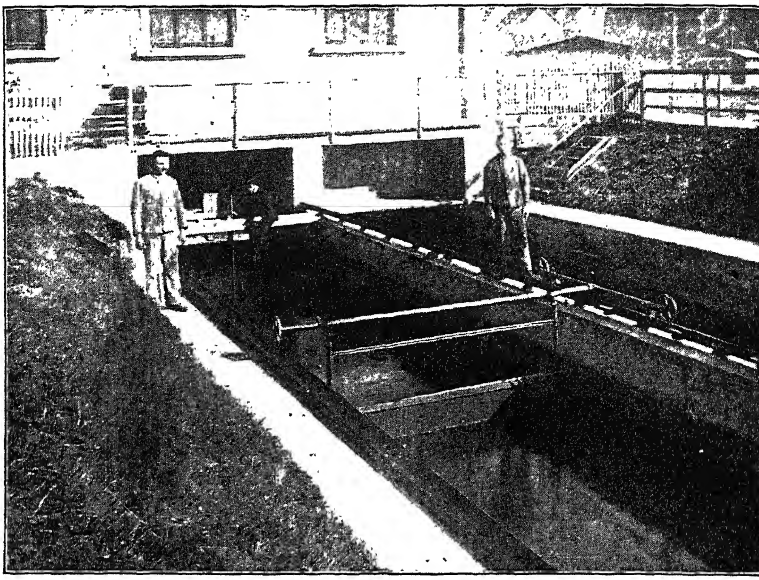
The method of measuring the flow of water by means of diaphragms or traveling "screens" was invented by Prof. Erick Andersson of the University of Stockholm about twelve years ago.* This method has been used to a considerable extent in Europe, particularly, by the large manufacturer of hydraulic turbines, J. M. Voith, of Heidenheim, Germany, but it is almost unknown in the United States. The Voith apparatus is shown in Fig. 263.

Among the advantages of the diaphragm method are its great accuracy and sensitiveness to velocities as low as a few hundredths of a foot per second, and the fact that the results are known immediately so that measurements can be repeated at once in case they fail to check.

The Pitot Tube. — The Pitot tube has long been used for measuring the velocity of water, but not until recently have its possibilities been fully appreciated. Any pipe with its stem vertical and its lower end bent into the direction of the current, so that the opening faces upstream, constitutes a simple form of Pitot tube. Many forms of tubes have been in use, but the

* The Diaphragm Method for the Measurement of Water in Open Channels of Uniform Cross Section, by C. R. Weidner, Bul. No. 672, University of Wisconsin, 1914.

shape of the orifice is no longer considered important. This was clearly demonstrated by White * in 1900.



Courtesy University of Wisconsin.

Fig. 263. — Measuring Discharge with Traveling Diaphragm.

The Pitot tube indicates a head equal to the velocity-head of the water impinging on its orifice, plus any static head under which the given filament of water is flowing. It has been found that if h is the velocity-head indicated by the tube, the velocity of the water is substantially equal to 98 per cent of $\sqrt{2\,gh}$. It should be added, however, that the formula $v = c\sqrt{gh}$ instead of $v = c\sqrt{2\,gh}$ still has its adherents.

In making determinations of flow with the Pitot tube it is usually far more difficult to measure the pressure-head than the velocity-head. The old forms of Pitot tubes in which the pressure-head was determined by means of an orifice placed

* White, W. M., Jour. Assoc. Engr. Soc., 1901, Vol. XXVII, p. 35. See also Moody, L. F., Proc. Engr. Soc. of Western Penn., 1914, Vol. XXX, p. 279; and Groat, B. F., *ibid.*, p. 324.

parallel to the direction of the current and alongside of the dynamic orifice were particularly subject to error.

When the flow of water is turbulent, the Pitot tube records the mean velocity-head which corresponds to the mean of the squares of the instantaneous velocities.

For best results the Pitot tube should not be rated by drawing it through still water but by comparing the known discharge of a pipe line, a Venturi meter throat, or a jet, with the discharge determined by means of the Pitot tube on the basis of the area of the cross section of the stream of water measured and the distribution of velocities in the cross section as ascertained by means of "traverses" with the tube.

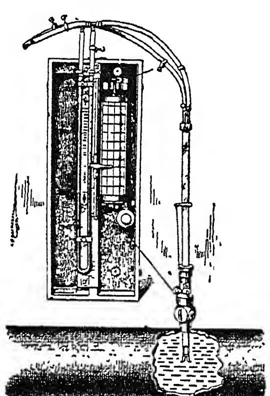


FIG. 264. — Cole Pitometer.

The Pitot tube finds its most common application in the measurement of the flow of water in pipes. A form of tube with a recording device, known as the Cole Pitometer, illustrated in Fig. 264, is most commonly used for this purpose.

The Venturi Meter. — Perhaps the simplest device for measuring the flow of water is the Venturi meter, invented by Herschel in 1886. The essentials of the Venturi meter are shown in Fig. 265. The area of contracted section or "throat" is from $\frac{1}{4}$ to $\frac{1}{9}$ of the area of the pipe line. At the throat of the meter the velocity is increased in proportion to the decrease in area and part of the pressure-head is transformed into velocity-head. The difference between the indicated pressure-head in the pipe and that at the throat of the meter represents the velocity-head corresponding to the known increase in velocity caused by the reduction in cross-sectional area, plus a small amount of head lost in friction. The discharge of the meter is given by the equation:

$$Q = CA_t \sqrt{\frac{2gh}{1 - \left\{\frac{A_t}{A_p}\right\}^2}}$$

where h is the difference in pressure-heads at the section of the meter where the area is A_p and that at the throat where the area is A_t. The coefficient c varies from .97 to .99.

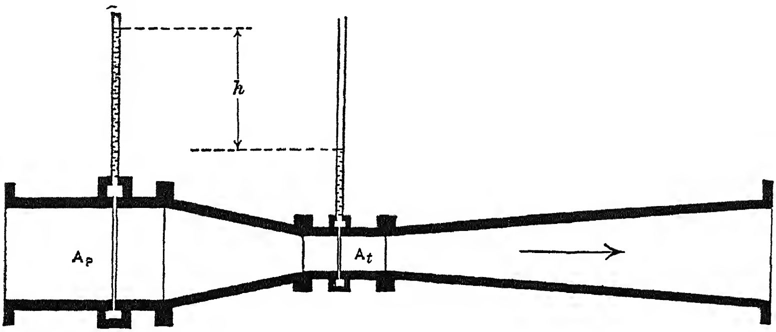


FIG. 265. — The Venturi Meter.

The greater the contraction at the throat of the meter the greater the difference in pressure-heads and, hence, the greater the accuracy of the readings but also the greater the friction loss. This loss, however, is very small, although it is continuous. It is independent of the pressure in the pipe line or penstock; consequently the power loss becomes relatively smaller with increased head. It varies from about one tenth to one half of one per cent. The loss in the meter can be reduced to a minimum by tapering the diverging portion very gradually, because eddy losses are much more likely to occur in the diverging portion of the stream than in the converging portion. This fact is well illustrated in nature by the shape of a fish. The improved construction of modern large-size meters, resulting in small losses, has led to an increasing use of this device for measuring the flow of large quantities of water.

Large Venturi meters are commonly built up in three parts. The approaches are often built of concrete, wood stave, or riveted-steel pipe, the throat, only, being a carefully machined

casting, usually of bronze. Meters as large as 18 feet in diameter are in successful operation. Venturi meters themselves require neither attention nor repairs. The only maintenance required is for the small upkeep of the recording devices where a continuous record of flow is secured.

Hazen* has called attention to the fact, that, since Venturi meters indicate velocity-head, or the square of the instantaneous velocity, they will over-register from 3 per cent to 5 per cent on lines when great and rapid fluctuations occur in the flow.

This, of course, is due entirely to the recording device. Under ordinary conditions of turbulence, the over-registration is negligible.

Salt Velocity Method. — A new method of water measurement that has been found both simple and accurate, particularly for penstock measurements, is Allen's salt velocity method.†

This method is similar in principle to the color velocity method. The velocity of flow is measured by means of charges of salt introduced at one point in the pipe line or flume and detected at another point, a known distance further, by means of electrical instruments. The presence of salt greatly increases the conductivity of water and therefore makes its detection, by electrical measurement, possible. The area of cross-section is determined by physical measurement and the product of area times velocity gives discharge.

Like every other method, its results depend upon the accuracy and refinement with which it is used. After several years' application in the laboratory and in power plants the authors of the paper cited concluded as follows, particularly with reference to the commercial tests at Grand Mere, Quebec.

> "165. These tests proved that when properly conducted the salt velocity method of water measurement checks the discharge by weight, which is the most accurate known method of measuring water. For short pipes the following items of apparatus and methods of computation were proven or confirmed:

* Hazen, Allen, Engineering News, August 17, 1916, p. 293.

† Allen, Charles M. and Taylor, Edwin A., "The Salt Velocity Method of Water Measurement," Trans. Am. Soc. M. E., 1923, p. 285.

"*a.* That a tight, quick-closing pop valve is most suitable for salt injection.

"*b.* That other methods of salt injection can be used, but correct results are obtained only by applying an arbitrary and consequently inaccurate correction.

"*c.* That it makes very little difference what form of electrode is used at the introduction when the salt-injection pipe is very close.

"*d.* That screens or grids are ideal for both introduction and final electrodes.

"*e.* That an improved plate construction with proper spacing for the final electrodes gives very accurate results.

"*f.* That a traverse with short final electrodes gives equally accurate results.

"*g.* That the same electrodes held at a fixed point, determined by the traverse, also show accurate results.

"*h.* That computations based on the center of area as determined by a watt-hour meter and a series of jump-spark dots simplify the work and give accurate results.

"*i.* That tests can be repeated indefinitely and still check.

"*j.* That the apparatus and methods of computation used in the commercial tests were proven to be theoretically and practically correct, and the results obtained were accurate and reliable.

"166. And finally, the authors believe that the salt velocity method of water measurement is correct in theory and in practice, that it is applicable to any form or size of flume, pipe, or penstock, and that, in a few years, its simplicity and accuracy will make it an accepted standard method of water measurement."

The Gibson Method. — Another recent development in water measurement, named after the originator and inventor of the patented apparatus required for its use, is the Gibson Method.* This method is particularly applicable to waterwheel efficiency measurements. It requires a valve or gate for quickly changing the flow of water in the pipe line or penstock. The velocity is determined from the change in pressure in a given time, resulting from a change in gate opening. Frequent tests may be made at relatively small expense to determine operating conditions.

STREAM-FLOW DATA FROM WATER-POWER PLANTS

It is often possible to extend the available records of stream flow by utilizing records of water levels above and below dams.

* Gibson, Norman R., "The Gibson Method and Apparatus for Measuring the Flow of Water in Closed Conduits," Trans. Am. Soc. M. E., 1923, p. 343.

The flow over dams can be computed by means of the formula:

$$Q = clH^{\frac{3}{2}},$$

in which c is a coefficient varying from about 3.0 for unfavorable spillway profiles and small values of H to about 3.8 for the best curved profiles and large values of H; l is the length of spillway crest in feet; and H the head on the crest, measured in quiet water back of the dam. When flashboards are in use a value of 3.33 should be used for c.

In case of end contractions the length of the spillway should be reduced by .1 H for each end although in long spillways this correction is negligible. When the cross-sectional area of the stream is about 5 times the area of the over-falling sheet of water the effect of velocity of approach is negligible.

The flow through submerged sluice gates is usually proportional to the square root of the head on the center of the opening. The coefficient of discharge will vary greatly with the shape of opening and the approach, but will lie between .60 and .95, usually approaching the lower value.

The flow through power houses can be determined from records of power output or gate opening, and head- and tail-water levels by rating the installation by actual meter measurements or by using the manufacturer's rating of the turbines, or Holyoke tests if these are available. When a turbine installation has once been well rated for various heads and gate openings, good records of stream flow can be secured if a continuous record of operation is kept at the plant.

WHERE STREAM-FLOW DATA ARE PUBLISHED

The principal sources of stream-flow data in the United States are the publications of the Water Resources Branch of the Geological Survey. This Branch was maintaining 1741 stations in 1914, and while in most cases the records extend back only a comparatively few years much extremely valuable information has been collected by uniform methods.

Other important sources of information are the U. S. Census Bureau, the U. S. Weather Bureau, the U. S. Army Engineers, the reports of State and City officials and Special Commissions.

Data for Canada are being published by the Dominion Water Power Branch, Ottawa, Canada.

These various sources of information should always be consulted by the engineer before undertaking to make his own measurements.

CHAPTER XI

SUPPLEMENTING STREAM-FLOW DATA

Unreliability of Short-Term Means. — On comparatively few streams of the country do the records of discharge extend over a long term of years. Short-term records do not give the extremes of high and low flow unless by sheer accident such years have been included in the term over which observations extend. Short-term records, moreover, do not give a satisfactory value for mean utilizable flow. In the last analysis, it is usually necessary to supplement the observed stream-flow data with computed values based on rainfall and other physical data, in order to arrive at a probable maximum, minimum, and mean utilizable flow for any given stream.

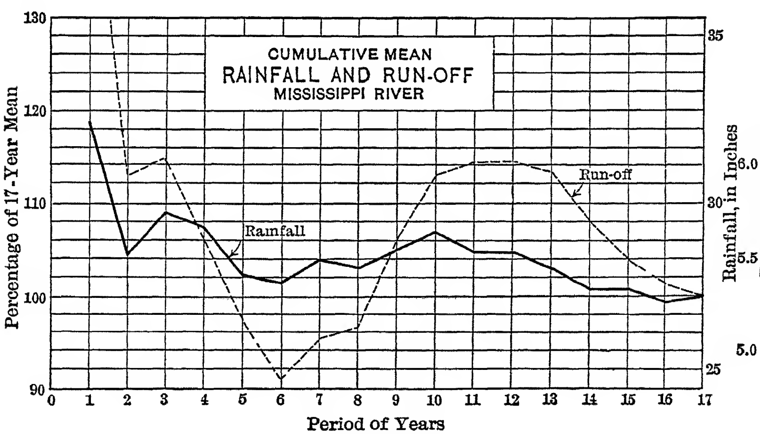


FIG. 266.

The curves of Figs. 266 to 268 show the annual and periodic variations in rainfall and runoff on the Tohickon Creek and the Mississippi River watersheds.

The curves of cumulative mean rainfall and runoff represent, at every point, the mean of all the annual values preceding. It is interesting to note that on the Mississippi River watershed

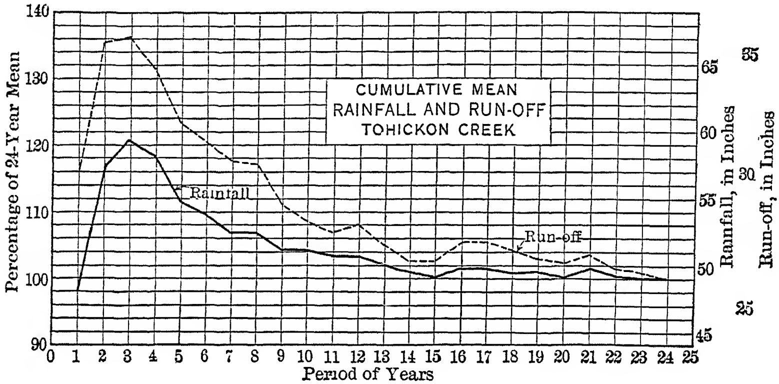


FIG. 267.

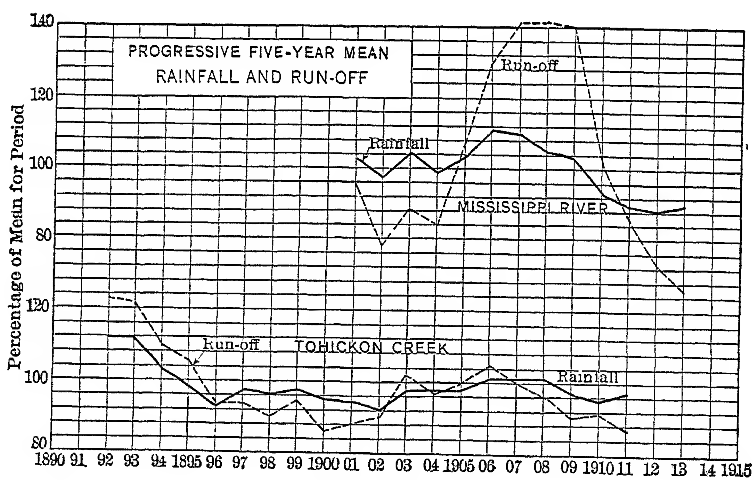


FIG. 268.

the 12-year mean runoff differs from the 6-year mean by more than 20 per cent. The 12-year mean rainfall, however, differs from the 6-year mean by only a small percentage. On the Tohickon Creek watershed the 5-year mean rainfall is 111 per cent of the 24-year mean, and the 5-year mean runoff is 123

per cent of the long-term mean. Though the variation in runoff is proportionately very much larger than the variation in rainfall, the actual variation in inches of rainfall and runoff is practically the same for the Tohickon Creek watershed, but the variation in inches of rainfall is very much greater than the variation in inches of runoff on the Mississippi River watershed. This difference exists on all watersheds having similar differences in annual rainfall and in evaporation and transpiration losses. On the Tohickon Creek watershed, the normal annual rainfall is sufficient to supply the needs of evaporation and transpiration; consequently, speaking in very approximate terms, most of the rainfall in addition to those needs appears as runoff, as has been pointed out frequently in the past. On the Mississippi River watershed, however, and throughout the greater part of the United States, the normal rainfall is insufficient to supply the needs of transpiration and evaporation at the prevailing temperatures; consequently, a large portion of any increased rainfall goes to supply unsatisfied needs of transpiration and evaporation, and hence a comparatively small portion of the increased rainfall, within certain limits, appears as runoff.

Sargent * comments briefly on long-term variations in stream flow on the Croton and Hudson rivers. It appears from these records, in so far as low water is concerned, that the rate of flow for the 5 driest months at Mechanicsville, on the Hudson River, was lowest in 1908 and highest in 1905. It was about one third as much during the former year as during the latter. It also appears that the rate of flow which occurred 70 per cent of the time during the 5 years, 1909 to 1913, was only a little more than one half of that which occurred 70 per cent of the time during the 26 years from 1888 to 1913, even though the extreme minimum rate of flow was practically the same in the two periods.

Fig. 268 shows the progressive 5-year mean rainfall and run-

* Engineering News, December 3d, 1914.

off for the Mississippi River and Tohickon Creek watersheds. These curves bring out forcibly the great differences which exist, particularly in runoff, between the average values derived from short-term — that is, in this case, 5-year — records.

If the conclusion as to mean annual runoff for the Mississippi River watershed were based on the 5-year mean ending in 1902, during which period the rainfall averaged 98 per cent of the mean for the 17-year period, this conclusion would be 20 per cent too low. If the conclusion were based on the 5-year mean ending in 1909, during which period the rainfall was 104 per cent of the mean for the 17-year period, the figure would be 40 per cent in error. If the conclusion were based on the 5-year period ending in 1913, during which period the rainfall was about 10 per cent below normal, the value adopted would be nearly 35 per cent too small. The maximum variation in 5-year means of runoff within the 17-year period over which the records used here extend is about 75 per cent.

Even though on a small watershed such as that of Tohickon Creek, the fluctuations are not as great as they are on the Mississippi, nevertheless, very substantial differences exist between the 5-year mean rainfall and runoff and the 24-year mean.

Comparative Hydrographs. — It must be apparent from the hydrographs of streams presented in the foregoing pages that conclusions respecting the flow of one stream, based upon hydrographs of that of another, even though an adjacent one, are usually subject to gross errors. Little reliance can be placed upon results secured in this manner unless the characteristics of the two watersheds are identical. This, however, is seldom the case; consequently, comparative hydrographs are of little value for supplementing stream-flow data.

Methods of Computing Runoff. — From time to time various curves and formulas designed to give the annual yield of water from any given watershed, and its distribution through the year, have been presented. Perhaps the most common expression of these quantities has been in terms of percentage of pre-

cipitation. Whenever this method has been adopted, great variations in runoff, for the same quantities of precipitation, have been noted. In fact, the lack of direct relationship between rainfall and runoff is a fact of common observation among those who have made a study of such data. Runoff, for a given month, considerably in excess of the rainfall for the same month, is not an exceptional occurrence on many streams of the country. For the same annual rainfall the annual runoff occasionally varies by nearly 100 per cent on the same stream.

These facts are well illustrated by Fig. 269.* The runoff for April, in Fig. 269, shows a variation of from 5 to 200 per cent of the rainfall on the same watershed. Moreover, the high percentage is for the lower rate of rainfall. The runoff for September shows a variation of from 2 to 140 per cent of the rainfall for practically the same precipitation on the same watershed. The annual runoff for one of the streams on Fig. 269 varies from 6.7 to 11.97 inches, or about 80 per cent for practically the same annual rainfall.

In attempting to express the relationship between rainfall and runoff, Vermeule† used a constant plus a percentage for the several months of the year, and varied this relationship on different watersheds with the mean annual temperature.

Justin‡ expressed annual runoff by an equation consisting of a coefficient (which varied with slope and mean annual temperature for different watersheds) multiplied by the square of the annual rainfall.

Babb § used curves giving the monthly runoff to be expected from any given watershed in the various parts of the country, in terms of a percentage of the total annual runoff. The latter was computed from the annual rainfall by using a percentage

* Compiled from "The Flow of Streams and the Factors That Modify It," by Prof. D. W. Mead, Univ. of Wis.

† Water Supply of New Jersey, 1894; and Annual Report, State Geologist of New Jersey, 1899. See p. 450 for further discussion of Vermeule's equations.

‡ Trans. Am. Soc. C. E., Vol. LXXVII, p. 346.

§ Trans. Am. Soc. C. E., Vol. XXVIII, p. 323.

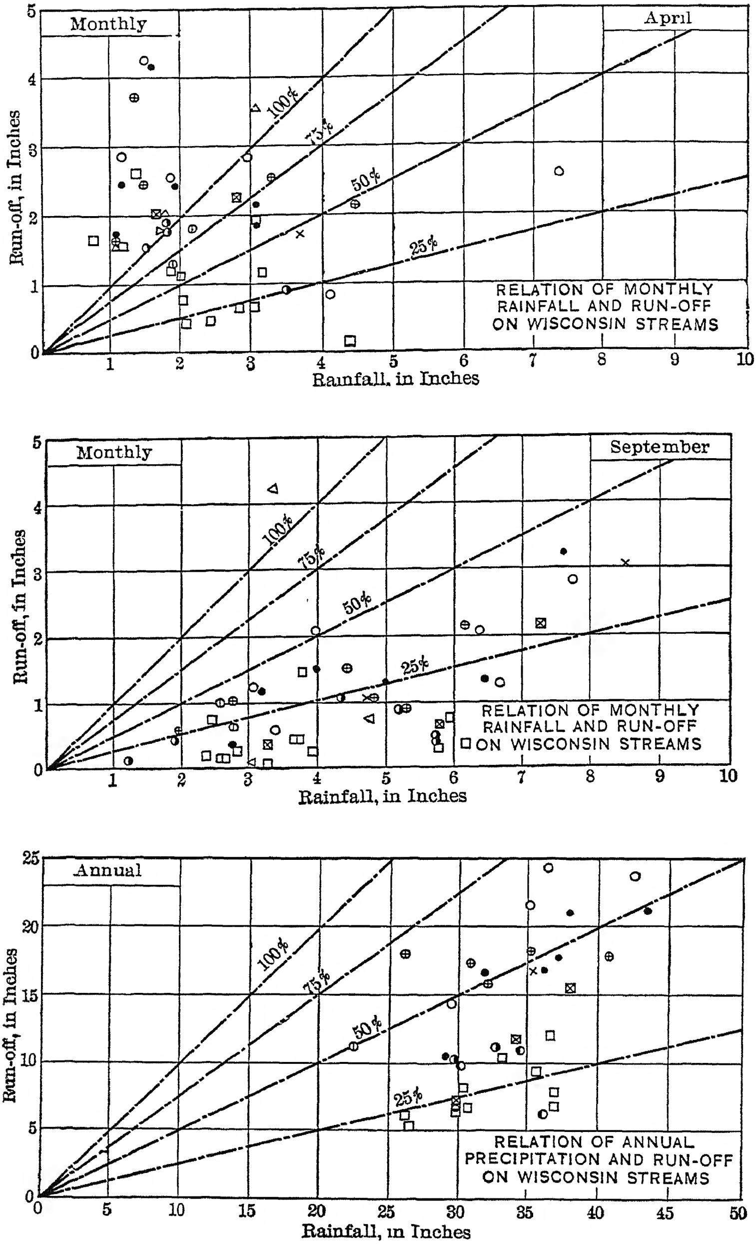


FIG. 269.—Lack of Relation between Rainfall and Runoff (after Mead).

relationship derived from a study of the mean observed relation between rainfall and runoff on a number of streams in various parts of the country.

Rafter * used curves, which, in general, are graphs of an exponential equation, for the purpose of showing the relation between rainfall and runoff by "storage," "growing," and "replenishing" periods.

Newell † expressed the general relationship between rainfall and runoff by two typical curves, one for streams in mountainous regions and the other for streams draining basins with broad valleys and gentle slopes.

Other writers have held that 20 inches of rainfall are required to supply evaporation and transpiration losses, and that practically all precipitation greater than 20 inches appears as runoff.

Although the subject of stream flow has been ably discussed by the men just mentioned, the author cannot refrain from expressing the belief that the relations between rainfall and runoff, indicated by the curves and formulas just referred to, are, in a varying degree, generalizations which bring out class likeness but obscure the individual characteristics of runoff from different watersheds, resulting from differences in the character and distribution of the rainfall, and the effect of temperature, vegetal cover, topography, soil, and subsoil on the disposal of rainfall.

In consequence, the author has worked up a "rainfall loss" or "hydro-physical" method of computing stream flow. The essentials of this method were first publicly presented in an address before the College of Engineering of the University of Minnesota about five years ago. A more detailed presentation was made in a paper before the American Society of Civil Engineers, printed in the 1915 Transactions, to which the reader is referred. The material of this paper is being freely drawn upon in this discussion.

* Water Supply and Irrigation Paper No. 80, U. S. Geol. Survey.
† Fourteenth Annual Report, Part 2, 1892–1893, U. S. Geol. Survey.

Considering the number of streams in the United States the discharge of which is of industrial importance, the number of stations at which stream flow is being measured is comparatively small, and the periods for which records are available are relatively short. If it takes from 30 to 40 years to secure an accurate measure of the mean annual rainfall at any given place, it is reasonably certain that the true means and extremes of runoff are compassed between at least as wide limits. Precipitation and temperature are being observed in the United States at nearly 6000 stations. Stream measurements are being made by Federal and State authorities and private parties, together, at about one fourth as many stations.

Notwithstanding the valuable work being performed by these organizations on all too meager appropriations, relatively few stream-flow data are available. For most streams only short-term records have been secured, covering by no means the extremes of high and low flow, or giving a dependable mean flow. If such measurements of stream flow as are available can be supplemented by reasonably accurate computed values, so as to give a long-term record of fair reliability, and covering more nearly the extremes of high and low flow, some of the uncertainty often attending efforts toward industrial utilization of the flow of streams and protection against floods may be eliminated.

Vermeule's Equations. — Vermeule's first general equation for annual runoff was: Runoff = Rainfall − (15.50 + 0.16 Rainfall) (0.05 Mean Annual Temperature − 1.48).

Later he modified this equation into: Runoff = Rainfall − (11 + 0.29 Rainfall) (A factor "*M*" varying from 0.77 for a Mean Annual Temperature of 40 degrees, to 1.51 for a Mean Annual Temperature of 61 degrees).

With his original equation for the annual yield of the Sudbury, Croton and Passaic River Basins, Vermeule used the following equations for the monthly evaporation and transpiration losses:

Dec.	losses = 0.42 + 0.10 Rainfall	April	losses = 0.87 + 0.10 Rainfall
Jan.	losses = 0.27 + 0.10 Rainfall	May	losses = 1.87 + 0.20 Rainfall
Feb.	losses = 0.30 + 0.10 Rainfall	June	losses = 2.50 + 0.25 Rainfall
March	losses = 0.48 + 0.10 Rainfall	July	losses = 3.00 + 0.30 Rainfall

Aug. losses = 2.62 + 0.25 Rainfall	Oct. losses = 0.88 + 0.12 Rainfall
Sept. losses = 1.63 + 0.20 Rainfall	Nov. losses = 0.66 + 0.10 Rainfall
	Total Annual Loss = 15.50 + 0.16 Rainfall

Vermeule did valuable pioneer work but he did not go far enough. The percentage of summer rainfall lost in evaporation is not a constant. Obviously a greater percentage is evaporated from light showers than from heavy downpours. A greater percentage is evaporated if the months of heavy rainfall are hot than if they are cool, even though the mean annual temperature is the same. Transpiration losses vary with monthly temperature and rainfall. For years of *average* meteorological conditions Vermeule's equations give reasonably accurate results, but for abnormal conditions they lead to large errors because they do not recognize some very influential factors. For example, for 28 inches annual rainfall with 44 degrees mean annual temperature, corresponding approximately to St. Paul, Minn., conditions, Vermeule's last equation (applicable to eastern streams) would reduce to:

Losses = 9.68 + .255 Rainfall = 16.83 inches, and the author's method of estimating losses discussed later, gives 8.4 + .26 Rainfall = 15.68 inches. This value is derived from the author's curves of Fig. 272 using mean temperatures and rainfalls for each month, and 8 inches annual transpiration loss. For years of unusual rainfall and temperature conditions, however, the two methods of estimating losses give widely divergent results.

The "Water Year." — Frequent comment has been made on the fact that the calendar year is an inappropriate and conventional period into which to divide time, from a hydrological viewpoint. A period of 12 months, beginning December 1 and ending the following November 30, has been used by many hydraulicians and called the "water year." This "water year" has again been divided into three periods, *viz.*, December to May, inclusive, constituting the "storage" period; June to August, inclusive, constituting the "growing" period; and September to November, inclusive, constituting the "replenishing" period. Although this division of time is more logical than the calendar year, efforts to express runoff as a percentage

of rainfall for each of these periods are considered by the author hardly less futile than efforts to express runoff as a percentage of the monthly or annual rainfall. This is true because the yield of a watershed, as previously stated, is a *residual* of the precipitation and not a *proportion* of it.

Fig. 270 * substantiates this view. The scale used in Rafter's diagrams for the growing and replenishing periods completely conceals the true lack of relationship between rainfall and runoff during these periods. At first glance one would conclude that the runoff during the growing and replenishing periods showed a much closer relationship to the rainfall than that of the storage period. On plotting the values for these two periods to a scale which results in a curve comparable to that used for the storage period, however, quite the contrary is found to be the case, as shown in Fig. 271.

During the storage period, the runoff varies from 12.8 to 22.3 inches, or practically 75 per cent for a rainfall of between 22 and 23 inches. During the growing period, on the same stream, the runoff varies from .72 to 3.07 inches, or 325 per cent for approximately the same rainfall. During the replenishing period the runoff varies from 3.76 to 1.58 inches, or 140 per cent for rainfalls of 13.11 inches and 12.89 inches respectively. The entire annual runoff from this watershed varies in 15 years from 12.69 inches for 39.70 inches of rainfall to 23.27 inches for 38.71 inches of rainfall, or practically 100 per cent for the same rainfall.

The author usually takes as his rainfall year, in northern latitudes, the 12-month period beginning November 1, and as the corresponding runoff year the 12-month period beginning the following March 1. Stream flow during the winter, in the northern half of Minnesota, for example, is almost entirely independent of the precipitation during these months, because such precipitation is practically all stored as snow. Stream

* Complied from Water Supply Paper No. 80, "The Relation of Rainfall to Run-Off," by George W. Rafter.

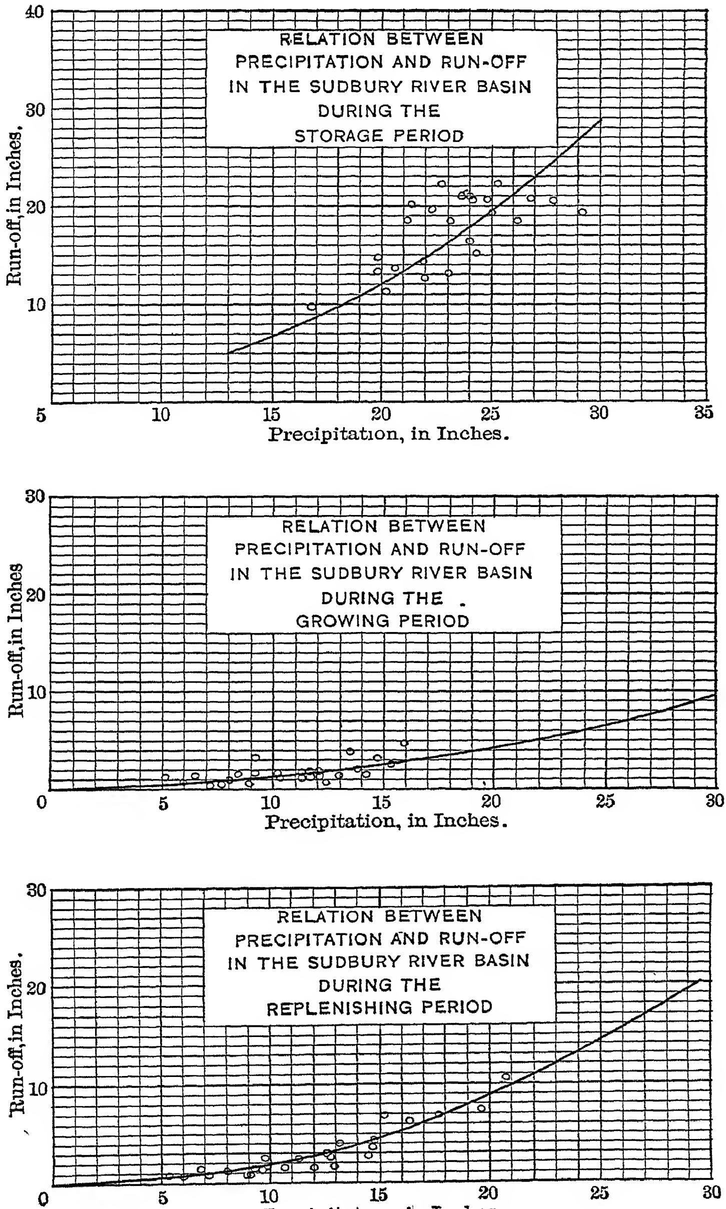


FIG. 270.—(After Rafter.)

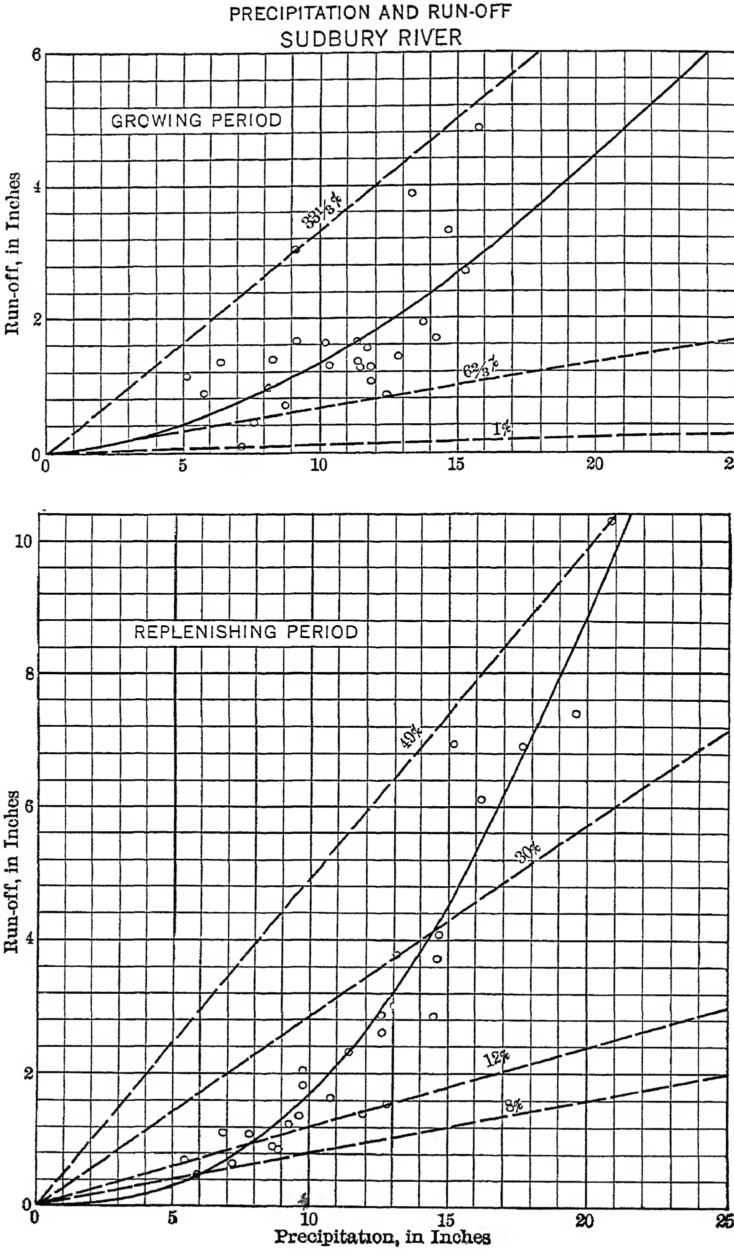

PRECIPITATION AND RUN-OFF
SUDBURY RIVER
GROWING PERIOD
33⅓%
6⅔%
1%
Run-off, in Inches
0
2
4
6
0
5
10
15
20
25
REPLENISHING PERIOD
49%
30%
12%
8%
Run-off, in Inches
0
2
4
6
8
10
0
5
10
15
20
25
Precipitation, in Inches

FIG. 271.

flow, in such latitudes, is dependent on the water stored in the ground and in lakes during the previous open seasons.

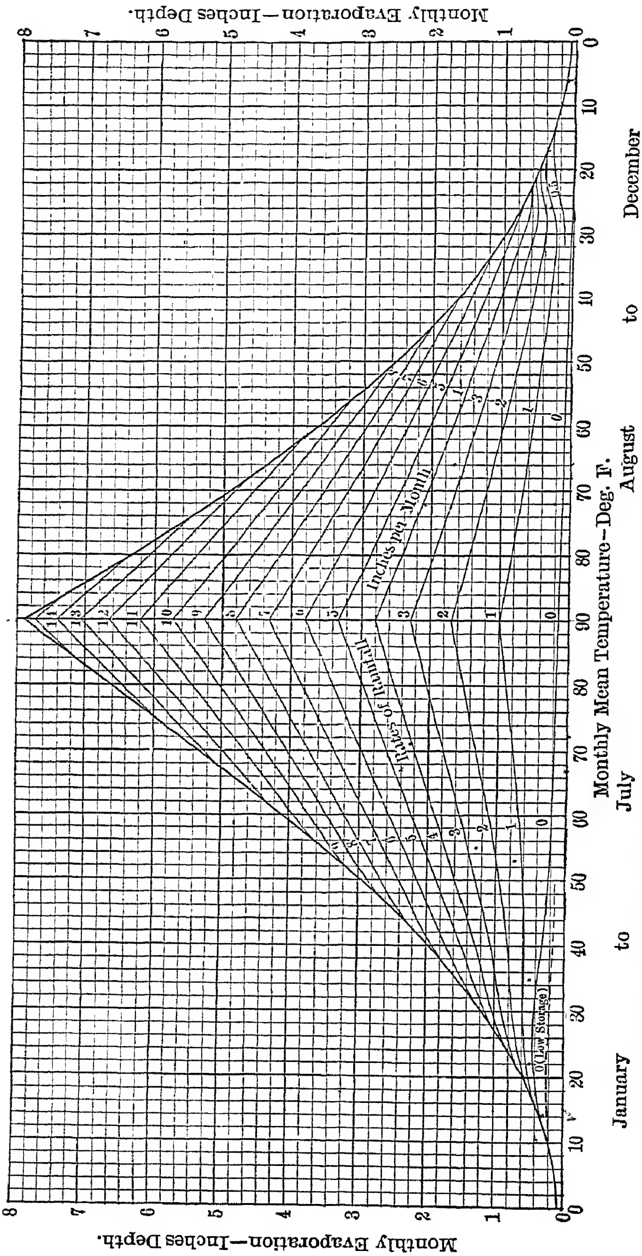
In the greater portion of the United States, a 12-month period beginning August, September, or October 1, when the ground and surface storage are both reduced to a minimum, affords a satisfactory "water year." Usually, however, the annual yield of a watershed, even in such "water years," is modified somewhat by ground storage.

The author computes the annual runoff entirely by calendar months, without any attempt to adhere to a division of the year into "storage," "growing," and "replenishing" periods, or into spring, summer, fall, and winter seasons.

The Author's Evaporation Curve. — The variation of evaporation from land areas with changes in seasons, monthly mean temperature, and monthly mean rainfall, based on the author's study of the subject, is summarized in the evaporation curve of Fig. 272.

In the fall, when the monthly temperature reaches 20 degrees, practically all the precipitation occurs as snow; consequently, evaporation for temperatures below 20 degrees is no longer dependent on precipitation after the ground has been covered with snow, but entirely on temperature. Full evaporation, corresponding to the given monthly temperature, is usually possible throughout the winter. After the temperature rises above 20 degrees, in spring, the evaporation again depends largely on available moisture, as determined mainly by precipitation. Nevertheless, a considerable constant evaporation is still possible, irrespective of precipitation, because a certain quantity of snow and ice is almost always present on the ground while the monthly temperature ranges from 20 to 35 degrees. After the snow has disappeared, there will still be a relatively large constant evaporation, irrespective of the rainfall, unless the winter precipitation has been distinctly deficient.

A gradual reduction in the constant evaporation has been assumed for the summer. It is realized, of course, that the



EVAPORATION FROM LAND AREAS FOR VARIOUS TEMPERATURES AND RATES OF RAINFALL.

FIG. 272.

constant evaporation during the summer depends, in a measure, on the rainfall of each previous month. In making detailed computations of evaporation losses, the constant evaporation is readily varied by one or two tenths of an inch, in accordance with apparent variations in storage. On some watersheds, when the fall precipitation is very low and the temperature remains above 30 degrees, the right-hand portion of the curve is used for January and sometimes also for February, that is, when the storage is practically exhausted and there is no snow on the ground, the constant of evaporation otherwise used practically vanishes and the evaporation is entirely proportional to the rainfall. In the same way, when the fall rains are copious and the ground-water supply is abundant, a constant of evaporation one or two tenths higher than that given by the curve may be used to advantage.

The portions of the limiting curve below temperatures of approximately 35 degrees represent evaporation from snow and ice surfaces. At the higher temperatures the limiting curve represents values somewhat less than the evaporation from shallow water. The quantity evaporated out of each inch of rainfall becomes less and less as the monthly precipitation increases, varying more rapidly at the lower than at the higher rates of precipitation.

To the values of evaporation, in inches of depth per month, as taken off the curve, a coefficient must be applied to reduce these quantities to actual evaporation from the given watershed. This coefficient ranges from about .95 to 1.25 for most watersheds of the Northwest and for similar ones elsewhere. Very sandy watersheds may require a coefficient as low as .60 and very impervious flat watersheds may require a coefficient in excess of 1.25. The coefficient to be used depends on topography, vegetal cover, soil, subsoil, humidity, and wind. An extremely high coefficient of evaporation (in excess of 1.25) would result from flat topography devoid of vegetation, moderately pervious, shallow soil underlain with impervious subsoil

or rock, low humidity, and high wind velocity. An extremely low coefficient (less than .95) would result from rugged topography, bare scanty soil underlain with rock, high humidity, and low wind velocity or extremely sandy soil. Between these limits the usual working values will be found. With a little experience, one can select coefficients for different watersheds with considerable accuracy.

The Author's Transpiration Curve. — The base values for total transpiration, in inches of depth, during the growing season on any given watershed, are selected with reference to the character of the vegetation and the length of the growing season on that watershed, giving consideration also to available sunshine. In the following computations a normal seasonal transpiration of about 9 inches has been assumed for small grains, grasses and other agricultural crops, 8 to 12 inches for deciduous trees, 4 inches for evergreen trees and 6 inches for small trees and brush The normal monthly distribution of this total seasonal transpiration is based mainly on temperature. To obtain actual transpiration in any given month, however, the values taken from the transpiration curve, Fig. 164, p. 263, after being multiplied by a coefficient, must be further modified on the basis of available moisture. Where precipitation minus evaporation for a given month is insufficient to meet the normal plant requirements for that month, the ground-water is drawn on to a varying extent, depending on the character of the root system of the given vegetation, the depth and character of the soil, and the quantity of surface soil storage, as determined by the precipitation minus losses for previous months.

Synopsis of Author's Method of Computing Annual Runoff

The main features of the author's method of computing runoff to supplement observed stream-flow data may be summarized as follows:

I. Collection of physical data.
  a. Rainfall and temperature data for stations on and near the given watershed from which monthly rainfall and temperature for the watershed are estimated. In case rainfall data are meager, charts showing isohyetals for the portion of the State in which the watershed is situated are of assistance.
  b. Data relating to wind velocity, relative humidity, and any other prominent weather characteristics.
  c. Data relating to topography, vegetal cover, soil, and subsoil, as affecting evaporation.
  d. Data relating to character and density of vegetation and length of growing season, with reference to temperature and hours of sunshine.
  e. Data relating to area of open water surfaces, swamps, and marshes.

II. Determination of losses.
  a. Evaporation from water area.
    1. Monthly evaporation corresponding to given temperature and season, taken off curve, Fig. 150, and multiplied by percentage of water surface, based on data under I-*e*, and coefficient based on data under I-*b*.
  b. Evaporation from land area.
    1. Determination of coefficient for given watershed, based principally on physical data under I-*c* and I-*b*.
    2. Determination of evaporation, in inches depth per month, corresponding to given monthly temperature and rainfall for given season of year, from curve of evaporation from land areas, Fig. 272, and multiplication of this value by percentage of land area and coefficient determined under II-*b*-1.
  c. Transpiration from land area.
    1. Determination of normal seasonal transpiration, based on physical data under I-*d*.

2. Determination of transpiration coefficient by finding ratio between seasonal transpiration determined from base curve of transpiration (Fig. 164) for the normal monthly temperatures for the given watershed, and the normal seasonal transpiration determined under II-*c*-1.
3. Determination of monthly transpiration by applying transpiration coefficient to monthly values taken off transpiration curve for given monthly temperatures, and modification of these monthly values on basis of rainfall, percolation, and storage.

III. Determination of total loss by summation of monthly losses from land and water areas, the deduction of these monthly losses from the monthly precipitation, and summation of these monthly residuals to give the annual yield of the given watershed, with or without correction of this annual total for fall surface runoff, or changes in ground and surface storage.

IV. Where the annual yield and its distribution throughout the year are both desired, additional curves similar to those for the Root River watershed, and computations similar to those given in Table 43, for the same watershed, must be made. When the more detailed computations, as here indicated, are carried out, it is possible to make more accurate estimates of transpiration during months of deficient rainfall, because more accurate values of soil and subsoil storage are available.

Fig. 273 is a relief map of the United States based on the maps published by the United States Geological Survey. Figs. 27, 28, 29, 67, 180 and 273 are of service in determining the evaporation coefficient and Figs. 67, 163 and 168 aid in determining the normal seasonal transpiration on any given watershed.

Computing Annual Yield. — The author's method of computing the annual yield in runoff from a watershed will be reasonably clear from the preceding synopsis, as the several stages are given in considerable detail. Large watersheds

FIG. 273.—Relief Map of the United States.

should be broken up into smaller units and the yield of each computed separately. Table 42 is a summary of the results of the application of this method to fifteen widely different watersheds. These data show a satisfactory correspondence between computed and observed runoff.* Preliminary computations of evaporation and transpiration losses are likely to be modified somewhat when the monthly runoff is computed.

TABLE 42. — OBSERVED AND COMPUTED PHYSICAL DATA FOR FIFTEEN WATERSHEDS

Name of watershed	Years of record	Evaporation coefficient	Area, in square miles	Observed and computed physical data — mean annual							
				Rainfall	Temperature	Evaporation	Transpiration	Total loss	Precipitation minus total loss	Computed runoff	Observed runoff
Mississippi	17	1.20	19,500	27 3	41	14 4	7 7	22 1	5 2	5 23	5 31
Little Fork......	5	1 10	1,720	23 9	37	11 2	6 9	18 1	5 8	5 80	
										*5 15	*5 13
Minnesota... .	5	1 25	6,300	22 7	43	14 1	7 5	21 6	1 1	1 1	.
									*0 77	*0 77	*0 70
Root.	6	1 225	1,560	31 4	45	16 5	8 9	25 4	6 0	6 10	
										*5 16	*5 20
Ottertail .. .	6	1 10	1,310	23 0	40	13 5	6 6	20 1	2 9	2 80	
										†2 66	†2 59
St. Croix. ..	11	1 05	5,930	30 0	41	13 1	7 0	20 1	9 9	9 90	9 60
Ohio .	14	0 875	23,820	41 1	51	14 8	5 8	20 6	20 5	20 50	22 00
Tohickon Creek.	24	0 90	102	48 9	51	16 7	7 0	23 7	25 2	25 2	26 10
James.	7	0 925	6,230	42 1	54	16 3	7 0	23 3	18 8	18 90	18 00
Roanoke. . . .	9	0 90	390	42 6	57	16 9	7 0	23 9	18 7	18 60	17 70
Tombigbee.. .	9	1 05	4,440	49 2	62	22 8	8 4	31 2	18 0	18 00	17 10
Colorado. .	10	1 20	37,000	26 9	66	17 7	8 1	25 8	1 1	1 06	0 74
Sacramento .	9	0 85	10,400	32 2	52	8 5	2 4	10 9	21 3	21 3	20 40
Pit ..	6	1 10	2,950	14 8	48	6 9	3 0	9 9	4 9	4 9	.. .
									*3 87	*3.87	*3 92
McCloud.	6	0 60	608	61 9	55	8 2	2 4	10 6	51.3	51 3	54 00

* Four years' records. † Five years' records.

Computing Monthly Runoff. — It is well to keep in mind, in comparing monthly computed stream flow with observed data, that both observed and computed runoff data for any given watershed are of service only as a basis for estimating the runoff which will probably occur in the future. An identical recur-

* See author's paper "Computing Runoff from Rainfall and Other Physical Data," Trans. Am. Soc. C. E., Vol. LXXIX, pp. 1056 to 1224, 1915.

rence of any given combination of meteorological phenomena on any one watershed is extremely improbable. In view of this fact, the complete daily, and, to a large extent, the monthly distribution of runoff, is of much less importance than the annual yield of a watershed, the probable extreme maximum flow, the extreme minimum and a reasonably accurate estimate of runoff below the limit of economical utilization for whatever purpose the stream flow is to be used.

Inasmuch as the low-water flow from most small watersheds is so extremely small as to be hardly capable of economical use except through storage reservoirs, the sudden fluctuations in stream flow below the maximum expected flood, with the reservoir filled, are of little consequence. Whether one inch of runoff occurs in a few days or in a few weeks is not of much consequence on such a watershed if all the available runoff can be held in the storage reservoir for gradual utilization. The engineer is usually much more interested in the total runoff from such a watershed, up to the point of economical utilization, than in the exact distribution of that runoff through the year.

Ability to compute the monthly distribution of runoff requires an understanding of all the factors affecting stream flow, heretofore discussed. It is also necessary to have rather complete data regarding the geological, topographical, and cultural conditions of the watershed and daily temperature and precipitation data. Next, curves of the type shown in Figs. 274 to 276 for the Root River, Minnesota, must be prepared. These curves may be based upon the results of a study of the available runoff data for the watershed under investigation or for a reasonably similar adjoining watershed, but should preferably be checked by at least short-term runoff records for the same watershed.

The curves of Fig. 274 show, in the first place, the approximate maximum quantity of snow which, when available, will melt at the given monthly mean temperatures. The other

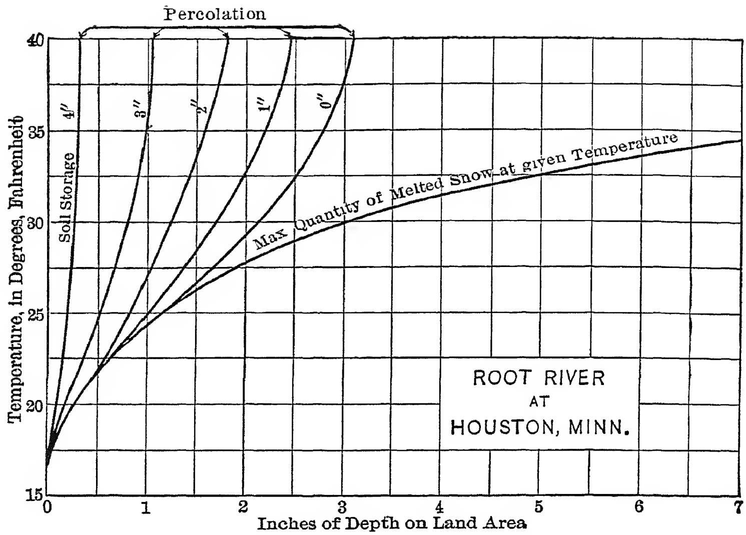


FIG. 274.—Relation between Temperature, Melted Snow, Soil Storage and Percolation.

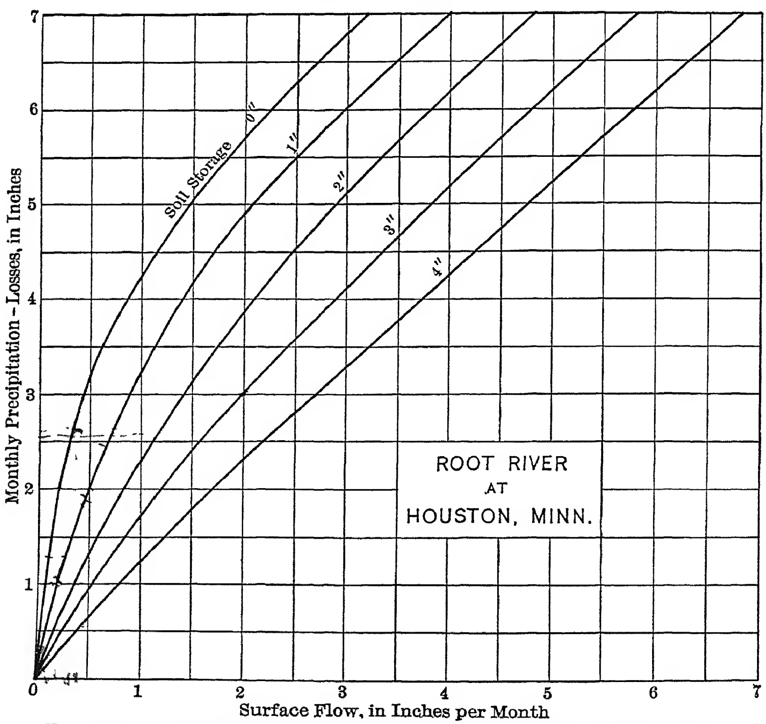


FIG. 275.—Relation between Residual Precipitation, Soil Storage and Surface Flow.

curves in Fig. 274 give the estimated quantity of this melted snow which will percolate into the ground under various conditions of soil storage. The drier and the more sandy the soil, even though frozen, the more melting snow it will absorb. A portion of the melted snow which does not percolate into the ground will immediately run off into the streams. Another portion will be retained for some time, part to appear as runoff

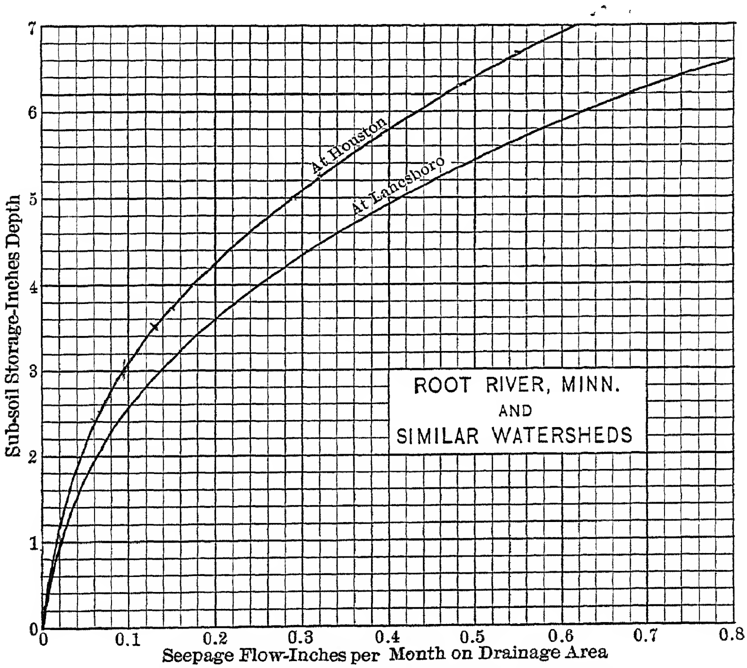


FIG. 276.—Relation between Sub-soil Storage and Seepage Flow.

later, and part to be gradually absorbed by the soil. The proportion retained for a time depends largely on topographic conditions. It may be treated substantially as precipitation minus losses for the following month, resulting from well-distributed rains.

The curves of Fig. 275 are to be used to aid in determining the quantity of surface runoff resulting from a given monthly "precipitation minus losses." Their application necessitates

the use of daily precipitation records, and allowance must be made for concentration and intensity of precipitation during the month. In Minnesota, less surface runoff will, in general, result from a given "precipitation minus losses" in spring and fall than in summer, because the rains are usually well distributed during the former seasons. Some latitude must be allowed and judgment exercised in the application of these curves.

On very sandy watersheds the curves of Figs. 274 and 275 having a value of 2 inches, for example, might have a value of 3 or 4 inches, and on very clayey watersheds these same curves might have a value of 1 inch or even 0.

The curves of Fig. 276 are to be used to determine the seepage flow for a given quantity of subsoil storage. On the Root River watershed moisture which has once passed down through the upper foot or two of soil will continue downward, as a rule, to join the subsoil storage and aid in maintaining stream flow. It is practically safe against return through the action of capillarity.

Two curves are given in Fig. 276, one for Lanesboro where the watershed area is 615 square miles and one for Houston where the watershed area is 1560 square miles. These curves have been applied to other watersheds in southeastern Minnesota and are applicable to similar watersheds elsewhere. The shape of similar curves for other watersheds depends mostly upon the topography, the character of the soil and subsoil, and the size of the drainage basin.

In order to show the application of the writer's method of computing the monthly distribution of annual runoff, the detailed computations for the Root River watershed at Houston, Minn., are given in Table 43.

TABLE 43.—DATA AND COMPUTATIONS FOR THE ROOT RIVER WATERSHED—(*Continued*)

Year	Month	Monthly temperature, in degrees, Fahrenheit	Monthly precipitation, in inches	Transpiration, in inches	Evaporation, in inches: From curve	Evaporation, in inches: Actual	Total loss, in inches	Precipitation minus total loss, in inches	Computed run-off, in inches, over watershed: Surface flow	Computed run-off: Seepage flow	Computed run-off: Total	Observed runoff: At Houston	Observed runoff: At Lanesboro	Storage over watershed, in inches: Monthly storage	Cumulative storage on first of month: Surface	Cumulative storage: Soil	Cumulative storage: Subsoil	Cumulative storage: Total	Notes
1911	Mar.	35	0.8	...	0.40	0.49	0.61	0.31	0.15	0.14	0.29	0.29	0.24	0.02	0.50	1.30	3.56	5.36	(9)
	Apr.	45	1.4	0.3	0.70	0.86	1.16	0.24	0.05	0.17	0.22	0.25	0.22	0.02		1.50	3.88	5.38	(10)
	May	64	5.4	1.6	2.50	3.06	4.66	0.74	0.15	0.15	0.30	0.32	0.33	0.44	..	1.70	3.70	5.40	(11)
	June	73	3.2	1.7	1.95	2.39	4.09	−0.89	0.10	0.14	0.24	0.27	0.21	−1.13	....	2.30	3.54	5.84	
	July	72	3.2	1.7	1.90	2.33	4.03	−0.83	...	0.12	0.12	0.21	0.11	−0.95	...	1.40	3.31	4.71	
	Aug.	68	6.0	2.1	*2.60	3.18	5.28	0.72	0.20	0.11	0.31	0.81	1.76	0.41	..	0.60	3.16	3.76	(12)
	Sept.	61	4.3	1.5	1.75	2.14	3.64	0.66	0.15	0.10	0.25	0.34	0.31	0.41	.	1.00	3.17	4.17	(13)
	Oct.	46	7.4	0.3	2.00	2.45	2.75	4.65	1.40	0.10	1.50	1.03	1.78	3.15	.....	1.50	3.08	4.58	(14)
	Nov.	25	1.9	......	0.40	0.49	0.49	1.41	0.30	0.20	0.50	0.38	0.47	0.91		3.50	4.23	7.73	(15)
	Dec.	25	2.8	......	0.50	0.61	0.61	2.19	0.60	0.29	0.89	0.65	0.82	1.30	0.70	3.00	4.94	8.64	(16)
1912	Jan.	−3	0.7	......	0.05	0.06	0.06	0.64	..	0.35	0.35	0.36	0.32	0.29	1.50	3.00	5.44	9.94	
	Feb.	14	0.4	......	0.30	0.37	0.37	0.03	..	0.31	0.31	0.28	0.25	−0.28	2.10	3.00	5.13	10.23	
											5.28	5.19							
	Mar.	23	0.9	......	0.50	0.61	0.61	0.29	0.60	0.27	0.87	0.92	1.46	−0.58	2.10	3.00	4.85	9.95	(17)
	Apr.	49	2.9	0.4	1.20	1.47	1.87	1.03	0.80	0.34	1.14	1.12	1.54	−0.11	1.00	3.00	5.37	9.37	(18)
	May	59	4.9	1.5	2.15	2.64	4.14	0.76	0.40	0.48	0.88	0.78	1.07	−0.12	....	3.00	6.26	9.26	(19)
	June	64	2.0	1.8	1.20	1.47	3.27	−1.27	...	0.45	0.45	0.40	0.40	−1.72	.	3.00	6.14	9.14	
	July	71	6.0	2.2	3.00	3.68	5.88	0.12	0.05	0.39	0.44	0.61	0.52	−0.32	....	1.70	5.72	7.42	(20)
	Aug.	67	3.5	2.0	1.70	2.08	4.08	−0.58	....	0.34	0.34	0.33	0.30	−0.92	...	1.70	5.40	7.10	(21)
	Sept.	61	2.0	1.2	1.00	1.22	2.42	−0.42		0.30	0.30	0.30	0.28	−0.72	.	1.10	5.08	6.18	(22)
	Oct.	50	1.9	0.4	0.70	0.86	1.26	0.64	0.10	0.26	0.36	0.31	0.29	0.28	..	0.70	4.76	5.46	
	Nov.	37	1.4	...	0.35	0.43	0.43	0.97	0.10	0.24	0.34	0.29	0.28	0.63	.	1.20	4.54	5.74	
	Dec.	25	1.7	......	0.40	0.49	0.49	1.21	0.10	0.22	0.32	0.24	...	0.89		2.00	4.37	6.37	(23)
1913	Jan.	16	0.5	......	0.40	0.49	0.49	0.01	....	0.20	0.20	0.20	0.18	−0.19	0.50	2.60	4.16	7.26	
	Feb.	14	0.8	.....	0.35	0.43	0.43	0.37	....	0.18	0.18	0.18	0.17	0.19	0.50	2.60	3.97	7.07	
											5.82	5.68							

* Most of rain fell in one day — evaporation reduced about 0.1 in.

(9) Maximum temperature on one day, 76 degrees.
(10) Last days of March warm, some runoff carried forward into April; rain well distributed during April.
(11) About ½ in. of rain, May 31st, and about 3 in. of rain, June 2d–4th.
(12) Most of rain in one day.
(13) Rain well distributed.
(14) Rain well distributed.
(15) Month cold, precipitation very well distributed.
(16) About 1 in. of rain on 10th.
(17) Month cold, except last week, which was quite warm.
(18) Rain well distributed.
(19) Rain very well distributed.
(20) Considerable rain on 9th–11th.
(21) Rain very well distributed.
(22) Rain very well distributed.
(23) About ½ in. of rain.

TABLE 43. — DATA AND COMPUTATIONS FOR THE ROOT RIVER WATERSHED

Year	Month	Monthly temperature, in degrees, Fahrenheit	Monthly precipitation, in inches	Transpiration, in inches	Evaporation, in inches: From curve	Evaporation, in inches: Actual	Total loss, in inches	Precipitation minus total loss in inches	Computed run-off, in inches, over watershed: Surface flow	Computed run-off: Seepage flow	Computed run-off: Total	Observed run-off: At Houston	Observed run-off: At Lanesboro	Storage over watershed, in inches: Monthly storage	Cumulative storage on first of month: Surface	Cumulative storage: Soil	Cumulative storage: Sub-soil	Cumulative storage: Total	Notes
1909	June	67	3.6	2.0	1.90	2.33	4.33	−0.73		0.45	0.45	0.45		−1.18		2.00	6.10	8.10	
	July	71	0.7	1.3	0.60	0.74	2.04	−1.34		0.38	0.38	0.33		−1.72		1.30	5.62	6.92	
	Aug.	74	7.9	2.4	3.75	4.60	7.00	0.90	0.30	0.32	0.62	0.69		0.28		0.00	5.20	5.20	
	Sept.	60	4.5	1.6	1.85	2.27	3.87	0.63	0.10	0.28	0.38	0.37		0.25		0.60	4.88	5.48	(1)
	Oct.	47	1.3	0.3	0.50	0.61	0.91	0.39	0.10	0.25	0.35	0.32		0.04		1.10	4.63	5.73	(2)
	Nov.	39	6.5	......	1.50	1.84	1.84	4.66	0.80	0.21	1.01	0.83		3.65		1.50	4.27	5.77	(3)
	Dec.	15	1.5	...	0.30	0.37	0.37	1.13	0.20	0.22	0.42	0.44		0.71	2.00	3.00	4.42	9.42	(4)
1910	Jan.	13	1.7	......	0.30	0.37	0.37	1.33	...	.	0.38	0.37		0.95	2.50	2.00	5.63	10.13	
	Feb.	12	0.3	....	0.30	0.37	0.37	−0.07	...	.	0.33	0.30	0.24	−0.40	3.80	2.00	5.28	11.08	
											4.32	4.10							
	Mar.	45	0.0	0.2	0.30	0.25	0.45	−0.45	0.70	0.29	0.99	0.83	1.48	−1.44	3.70	2.00	4.98	10.68	(5)
	Apr.	51	1.2	0.8	0.60	0.74	1.54	−0.34	0.10	0.40	0.50	0.40	1.04	−0.84	0.50	3.00	5.74	9.24	
	May	53	2.6	1.3	1.10	1.35	2.65	−0.05			0.42	0.37	0.38	−0.47		2.50	5.90	8.40	
	June	70	0.2	1.5	0.20	0.25	1.75	−1.55			0.36	0.28	0.28	−1.91		2.50	5.53	8.03	
	July	75	0.9	1.0	0.65	0.80	1.80	−0.90			0.31	0.24	0.24	−1.21		1.00	5.12	6.12	
	Aug.	70	4.1	1.4	2.10	2.57	3.97	0.13			0.27	0.25	0.32	−0.14		0.10	4.81	4.91	
	Sept.	60	3.5	1.2	1.50	1.84	3.04	0.46	0.05	0.24	0.29	0.33	0.40	0.17		0.20	4.57	4.77	(6)
	Oct.	53	0.7	0.3	0.35	0.43	0.73	−0.03		0.22	0.22	0.25	0.26	−0.25		0.60	4.34	4.94	
	Nov.	29	0.4	....	0.10	0.12	0.12	0.28	0.05	0.20	0.25	0.25	0.29	0.03		0.50	4.19	4.69	
	Dec.	19	0.5	......	0.25	0.31	0.31	0.19		0.18	0.18	0.23		0.01		0.70	4.02	4.72	
1911	Jan.	13	0.9	....	0.30	0.37	0.37	0.53	0.05	0.16	0.21	0.23		0.32	0.20	0.70	3.83	4.73	(7)
	Feb.	23	1.5	....	0.60	0.74	0.74	0.76	0.30	0.15	0.45	0.56	*0.20	0.31	0.70	0.70	3.65	5.05	(8)
											4.45	4.22							

(1) 6½ in. of rain in 5 days.
(2) 4 in. of rain in 3 days.
(3) About 2 in. of snow; last week quite warm.
(4) Some snow melted during first week of month.
(5) High temperature, latter part of month.
(6) Heavy rain Aug. 31st and Sept. 5th.
(7) A few warm days, 24th–25th.
(8) 12th-17th warm, about 1 in. of rain.

TABLE 43.—DATA AND COMPUTATIONS FOR THE ROOT RIVER WATERSHED—(*Concluded*)

Year and month		Monthly temperature, in degrees, Fahrenheit	Monthly precipitation, in inches	Transpiration, in inches	Evaporation, in inches		Total loss, in inches	Precipitation minus total loss, in inches	Computed run-off, in inches, over watershed			Observed run-off		Storage over watershed, in inches					Notes
					From curve	Actual			Surface flow	Seepage flow	Total	At Houston	At Lanesboro	Monthly storage	Cumulative storage on first of month				
															Surface	Soil	Sub-soil	Total	
1913	Mar.	27	3.2	....	0.90	1.10	1.10	2.10	1.50	0.16	1.66	*2.48	2.27	0.44	0.90	2.60	3.76	7.26	(24)
	Apr.	46	1.5	0.3	0.75	0.92	1.22	0.28	0.20	0.26	0.46	0.46		−0.18		3.00	4.70	7.70	
	May	56	5.4	1.3	2.25	2.75	4.05	1.35	0.25	0.30	0.55	0.38		0.80		2.50	5.02	7.52	(25)
	June	72	3.2	2.0	1.90	2.33	4.33	−1.13	..	0.34	0.34	0.28		−1.47		3.00	5.32	8.32	..
	July	72	5.3	2.1	2.80	3.43	5.53	−0.23	0.10	0.30	0.40	0.42		−0.63		1.80	5.05	6.85	(26)
	Aug.	72	2.6	1.7	1.50	1.84	3.54	−0.94	...	0.27	0.27	0.30		−1.21		1.40	4.82	6.22	
	Sept.	62	3.7	1.4	1.65	2.02	3.42	0.28		0.25	0.25	0.24		0.03		0.40	4.61	5.01	(27)
	Oct.	47	2.6	0.3	0.85	1.05	1.35	1.25	0.10	0.20	0.30	0.28		0.95		0.70	4.24	4.94	(28)
	Nov.	41	1.7	......	0.50	0.61	0.61	1.09	0.10	0.19	0.29	0.25	....	0.80	.....	1.80	4.09	5.89	(29)
	Dec.	31	0.2	....	0.08	0.10	0.10	0.10	......	0.20	0.20	0.26	.....	−0.10	.....	2.50	4.19	6.69	....
1914	Jan.	24	1.4	....	0.50	0.61	0.61	0.79	....	0.19	0.19	0.22	..	0.60	..	2.50	4.09	6.59	...
	Feb.	11	0.5	....	0.20	0.20	0.24	0.26	..	0.17	0.17	0.17		0.09	0.80	2.50	3.89	7.19	.
											5.08	5.74							

* Estimated from Lanesboro.

(24) The month of destructive storms, minimum temperature, 10th–15th above freezing—heavy rain on 14th.
(25) Precipitation well distributed — no heavy downpours.
(26) Rather heavy rains 4th–5th.
(27) Rain well distributed.
(28) Rain well distributed.
(29) No snow — rain well distributed.

NOTE. — The 1913 run-off figures are advance estimates furnished through the courtesy of the District Office, U. S. G. S., and are subject to revision for publication. Official data will probably be available very soon.

Summing up the monthly runoff figures, as computed in this way, gives a value for the annual runoff which is much more accurate, and differs somewhat, from the computed annual "precipitation minus losses."

On watersheds such as that of the Colorado River in Texas, where the precipitation is distributed throughout the year in a similar manner to that prevailing throughout the Northwest, but where temperatures are so high that evaporation losses absorb by far the greater portion of the rainfall, and where the demands of vegetation for moisture are never fully supplied, practically all of the stream flow consists of surface runoff. On these watersheds, where there is no well-defined water-table above the stream bed, the entire runoff results from heavy rains, commonly called "cloudbursts," over small areas. As the surface of the ground on such watersheds is usually very dry, percolation is not very rapid; hence some of the rainfall escapes over the surface of the ground as runoff before sufficient time has elapsed for it to be evaporated, or to be used by vegetation. On such watersheds the character of the soil is the principal factor determining the amount of runoff. This is well exemplified by the discharge records of the Smoky Hill, the Saline, the Republican, and the Loup Rivers in Kansas and Nebraska.

As the runoff from watersheds of this character is usually very small the results of computations are certain to be in error by a large *percentage* even though the absolute error in inches depth may be very small. The same criticism applies to short-term observations of stream flow on such watersheds. As the flow of streams draining these watersheds is dependent upon heavy rains, the irregularities in stream flow are always great. If the watershed is sandy the underflow may constitute a far more dependable water-supply than the surface flow of the streams.

CHAPTER XII

MODIFICATION OF STREAM FLOW BY STORAGE

Applicability Dependent Upon Cost

The extent to which stream flow can be modified by the storage of water is primarily dependent upon the relation between the quantity of water which must be controlled in order to produce the desired modification in flow and the opportunities for reservoir construction. This relation is well stated by Van Ornum * in the following words:

> "For example, a billion cubic feet of stored water will supply a city of one or two hundred thousand inhabitants for a year; or it will irrigate from 4000 to 10,000 acres of arid land for a season; or it will furnish more than a million horse-power-hours under a head of 40 feet; but it would double the volume of low-water flow of the Mississippi River at St. Louis for less than eight hours, and is exceeded by the flood discharge at the same place in one-quarter of an hour."

The practicability of reservoir construction for any given purpose is usually determined by the unit cost of storage. Often, however, a projected storage may be economical for a given purpose but so much more valuable for another as to make it desirable to give the latter object priority and to depend only upon incidental benefits to the former object. The unit cost of water stored in the large reservoirs of the world differs greatly, varying from a minimum of $5 per million cubic feet, estimated as the cost of storing 168 billion cubic feet on the Upper Ottawa River watershed, to $30,000 per million

* Van Ornum, J. L., The Regulation of Rivers, 1914, p. 57.

cubic feet as the cost of storing a half-billion cubic feet on the Wien River watershed for protecting the City of Vienna from destructive floods. The Upper Mississippi River navigation reservoirs, with 98 billion cubic feet capacity, cost about $18 per million cubic feet, and the Ashokan, New York City, water-supply reservoir, with a capacity of 17.65 billion, cost $718 per million. The reservoirs of Germany, constructed largely in the interests of navigation, cost from $500 to $1500 per million cubic feet of capacity.*

Reservoir Sites

Among the factors determining the desirability of reservoir sites are:

1. Location of site with respect to locality served.
2. Dependability of water-supply.
3. Character of reservoir bed and banks.
4. Character of site for impounding dam.
5. Effective depth of reservoir.

The relative importance of these factors depends mainly upon the purpose which the reservoir is to serve.

Location. — The first characteristic of a good reservoir site is, of course, a location as convenient as possible to the locality that is to be served, whether that service is for water-supply, water-power, navigation, irrigation, or for any one of the other purposes for which storage reservoirs are useful.

Water Supply. — Perhaps second in importance is a dependable water-supply. Seepage and evaporation losses are comparatively uniform, definite quantities for which allowance can be made in the scope of the project; but an unreliable and indefinite supply of water represents a great economic handicap. Under such conditions, provision must be made, in the structural features of the project, for both extremes of water-supply, with the consequent increase in cost and fixed charges. Spillway capacity must be provided so that exceptional flood inflow

* Van Ornum, J. L., The Regulation of Rivers, 1914, Chapter 1.

into the reservoir can be wasted without endangering the stability of the impounding structures. On the other hand, sufficient storage capacity must be provided to furnish the necessary water-supply in years, or even a series of years, of exceptionally low inflow. For the same reason that, in a given region, a small stream usually experiences greater irregularity in flow than a large one, a reservoir with a small tributary watershed has a more irregular and less dependable water-supply than one with a large tributary area. In other words, in any given region, a large storage project is usually more dependable than a small one.

Seepage and Evaporation Losses. — For any given water-supply, that reservoir whose bed and banks are most nearly impervious and whose depth is greatest, will suffer the smallest seepage and evaporation loss. For a given temperature, evaporation from the water surface of a reservoir is directly proportional to its superficial area. The percentage of stored water lost in evaporation, then, except for small changes in reservoir area with stage, is inversely proportional to the depth of the reservoir. An increase in the depth of water in a reservoir, however, results in a decrease in its temperature and, hence, in a decrease in evaporation loss per unit of area.

Seepage losses from a reservoir are dependent upon the character and the dip of the strata of material that constitute its bed and banks, and on the elevation of the water-table in the given locality. In the United States east of the Mississippi, reservoir sites are almost invariably located in natural depressions that have the water-table close to the surface of the ground. Moreover, in this region, the water-table in the bordering hills usually slopes toward the reservoir site. Under such conditions seepage losses are usually negligible, and some of the percolating water returns to the reservoir as seepage flow when the stored water is being withdrawn. In arid and semi-arid regions, on the other hand, the water-table is so far below the level of the ground that seepage losses from reser-

voirs usually amount to from 15 to 30 per cent of the entire supply. In such regions, the character of the reservoir bed and banks is far more important than when the water-table is high, and may overshadow in importance even the character of the site for impounding structures. Observed seepage and evaporation losses from a typical western reservoir are shown in Fig. 277.* On most western reservoirs seepage reduces with time on account of the raising of the water-table and the silting up of the porous bed and banks. In some instances, clay may be sluiced into the reservoir to reduce seepage losses. This has been proposed for the Cedar Lake Reservoir, Washington.†

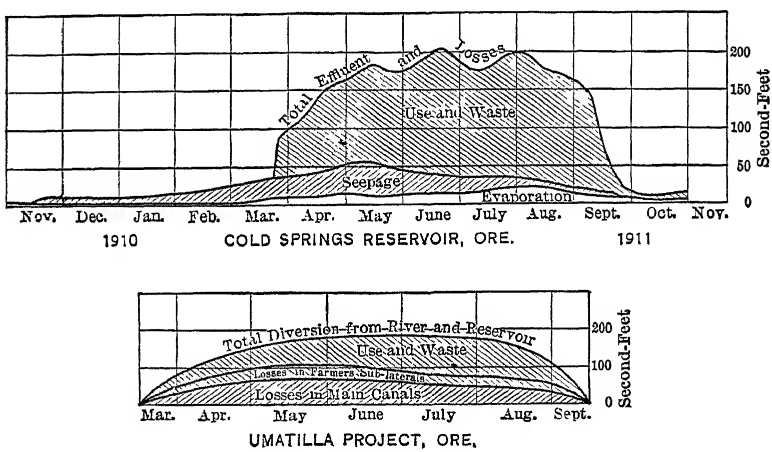


FIG. 277.—Seepage and Evaporation Losses from Typical Western Reservoir and Canal System.

Spillway Capacity.—The storage of water necessitates the use of impounding structures equipped with facilities for the discharge of excess water in time of extreme flood. Water that is available only once in ten, fifteen, or twenty years is not only useless but constitutes a source of danger. The history of wrecked dams and embankments in all parts of the country bears emphatic witness to its destructive powers.

* From a paper by E. G. Hopson, Trans. Am. Soc. C. E., 1913, p. 336.
† Engineering Record, Aug. 19, 1916, p. 228.

Dam Site. — A good dam site should provide good foundation material, preferably rock, and sufficient width to permit the installation of ample spillway capacity but no more. Where the construction of long earth embankments must be resorted to, the presence of clayey material and water, for the construction of the embankment by the hydraulic process, adds to the value of the site. The best sites are usually afforded by steep, narrow canyons, with rock bed and banks, which permit the construction of arch masonry dams, and the discharge of flood water without endangering the structure through erosion of the river bed on the downstream toe.

Sedimentation of Reservoirs. — While the possibility of the gradual reduction of reservoir capacity through the deposition of the silt carried by tributary streams must receive due consideration in each project, the danger of the silting up of reservoirs is usually negligible. Few artificial reservoirs are ever drained dry and natural lakes which are utilized in reservoir construction have such great storage capacity below the low-water level that the silting of centuries could hardly have an appreciable effect. The substantially unchanged existence of natural lakes in all parts of the world bears witness to this fact. Stabler * estimates that the system of reservoirs proposed for the Ohio River might silt up to the extent of 10 per cent of its capacity in about 800 years. Under exceptional conditions, however, an artificial reservoir may silt up quite rapidly as indicated by the Tuolumne River Reservoir at La Grange, Cal. The amount of silting which may be expected in a given time is directly proportional to the sediment carried by the tributary streams and the ratio of tributary watershed to reservoir area.

Effectiveness of Reservoir Storage

Losses in Conveying Channels. — When stored water is discharged from reservoirs and conveyed to the point of utilization

* Stabler, Herman, Engineering News, 1908, Vol. 60, p. 649.

through rocky channels, concrete-lined tunnels or canals, steel pipes or similar impervious conveyors, the losses are negligible, or limited to evaporation from the whole or part of the exposed surface, and all, or nearly all, of the reservoir discharge may be considered as effective. On the other hand, when stored water is discharged through natural or artificial channels with earth bed and banks the effective portion of the reservoir discharge may be relatively small. If the water-table lies below the channel, whether natural or artificial, the seepage loss is usually large. The principal factors influencing this loss are the character of the material constituting the bed and banks of the channel and the wetted perimeter of the channel. Another factor of more or less importance in different instances is the presence of vegetation on the banks of the channel and on the water surface itself. In a channel in which these three factors are constant an increase in the velocity of the water will reduce the *percentage* lost in seepage. When the velocity is increased, however, to a point where sedimentation is prevented and scouring results, no further economy is effected.

TABLE 44. — SUMMARY OF 323 SEEPAGE MEASUREMENTS (Fortier)

Capacity of canal, sec.-ft	Number of tests	Average loss per mile, per cent *
Less than 1	16	25.7
1 to 5	37	20.2
5 to 10	30	11.7
10 to 25	49	12 1
25 to 50	48	5 5
50 to 75	31	4.3
75 to 100	26	2.7
100 to 200	45	1.8
200 to 800	87	1.2
800 and over	14	1 0

* Loss per mile in per cent of total flow.

For typical soils of the arid region, consisting of about 16 per cent clay, 36 per cent silt, 19 per cent very fine sand and 18 per cent of fine sand, by volume, Fortier * gives the following

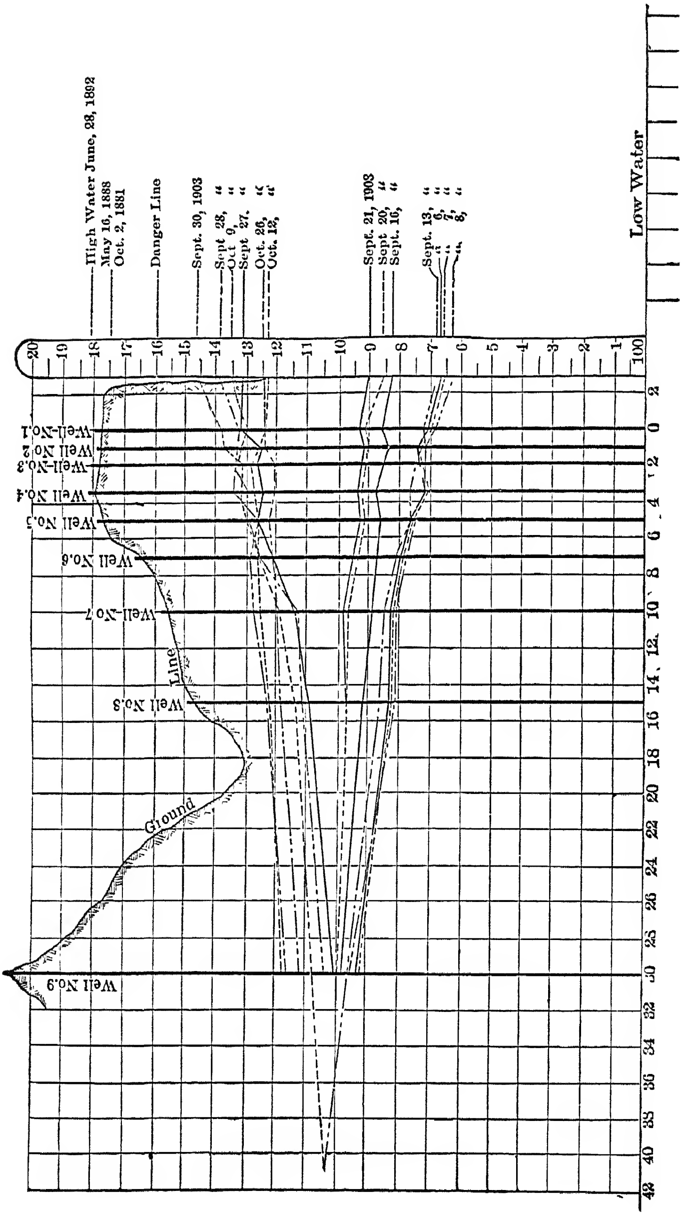
* Fortier, Samuel, Eng. News, 1915, Vol. 73, p. 1060.

average observed seepage losses in canals. The depth of the smallest ditches listed in this table varied from 2 to 4 inches and of the largest canals from 5 to 8 feet.

Loss through Temporary Ground-water Storage. — If the water-table lies above the channel, some of the discharged water will be temporarily lost through seepage. The effective portion is difficult to determine.

During the low-water seasons the stream flow, which it is desired to increase through the discharge of stored water, almost invariably consists entirely of seepage flow derived from the ground-water supply. Each succeeding reduction in river stage tends to maintain the prevailing slope of the ground-water surface toward the river channel, with a consequent continuation in flow of ground-water into the stream. If, now, the river stage be suddenly raised, or prevented from falling, through the discharge of stored water, the slope of the ground-water surface toward the stream will be reduced or even temporarily reversed and, hence, the discharge of seepage water retarded. This fact is well illustrated by Fig. 278.* This figure shows the elevation of the water-table at Muscatine, Iowa, for 3000 feet back from the Mississippi River during a rise and fall in river stage of about 9 feet. The material which constitutes the valley floor, and in which the ground-water table lies, consists of sand and fine gravel. Notwithstanding this fact, however, the changes which occurred in the level of the water-table, in this distance of 3000 feet, occupied several weeks. There were very heavy rains in the vicinity during the first two weeks of September, and light rains to October 6 to 7. Apparently the rains of September 1 to 15, amounting to about 5 inches in the vicinity of Muscatine, caused a rise in the water-table, as the result of percolation, approximately equal to the small rise in river stage. Then, from September 16 to 27, there was a pronounced rise in river stage accom-

* Hubbard, W. D., and Kiersted, W., Waterworks Management and Maintenance, 1907.



Water-level Observation, Muscatine, Iowa.

From "Waterworks Management and Maintenance," by Hubbard and Kiersted.

FIG. 278.—Effect of River Stage on Adjacent Water-table.

panied by only a small rise in the water-table. From September 27 to 30 the water-table rose almost as fast as the river, and continued to rise from that date until October 12, while the river was falling.

Retardation of Seepage Flow. — The extent to which the increase in river stage, resulting from the discharge of stored water from reservoirs, tends to retard seepage flow, and to defeat the object of reservoir discharge by temporarily wasting the water in replenishing the ground-water supply adjacent to the river channel, cannot be determined from the data at present available. Some of the factors influencing the extent of such action may, however, be considered. Perhaps the most important single factor is the length of river channel affected by the rise in stage caused by the reservoir discharge. A number of small reservoirs at the headwaters of different tributaries would affect a much greater length of channel than a single large reservoir on a single tributary. Streams deriving their seepage flow from a coarse, sandy or gravelly subsoil are affected more than those deriving their seepage flow from the finer sands or sand rock. Streams flowing in deep valleys through rolling country are relatively less affected than those flowing in shallow channels through comparatively flat land.

The seepage flow of Minnesota streams, during ordinary low-water years, amounts to about .3 inch in depth over the drainage area, per month. A reduction in flow from .3 inch to .1 inch per month on these streams would represent a lowering of the ground-water-table over the tributary watershed of about 1 or 2 feet. If the river stage is prevented from falling, a large portion of the ground-water adjacent to the channel will be prevented from reaching the stream, and the rate of flow from the remainder of the watershed subject to the direct influence of river stage will be reduced. As the effect of increased river stage, however, is limited to the channel through which the reservoir water is being discharged, and to the lower reaches of its tributaries, the retardation in seepage flow is

similarly limited to the local drainage area of the main stream and the lower reaches of its tributaries. The probable effect in each instance must be estimated on the basis of the best available data.

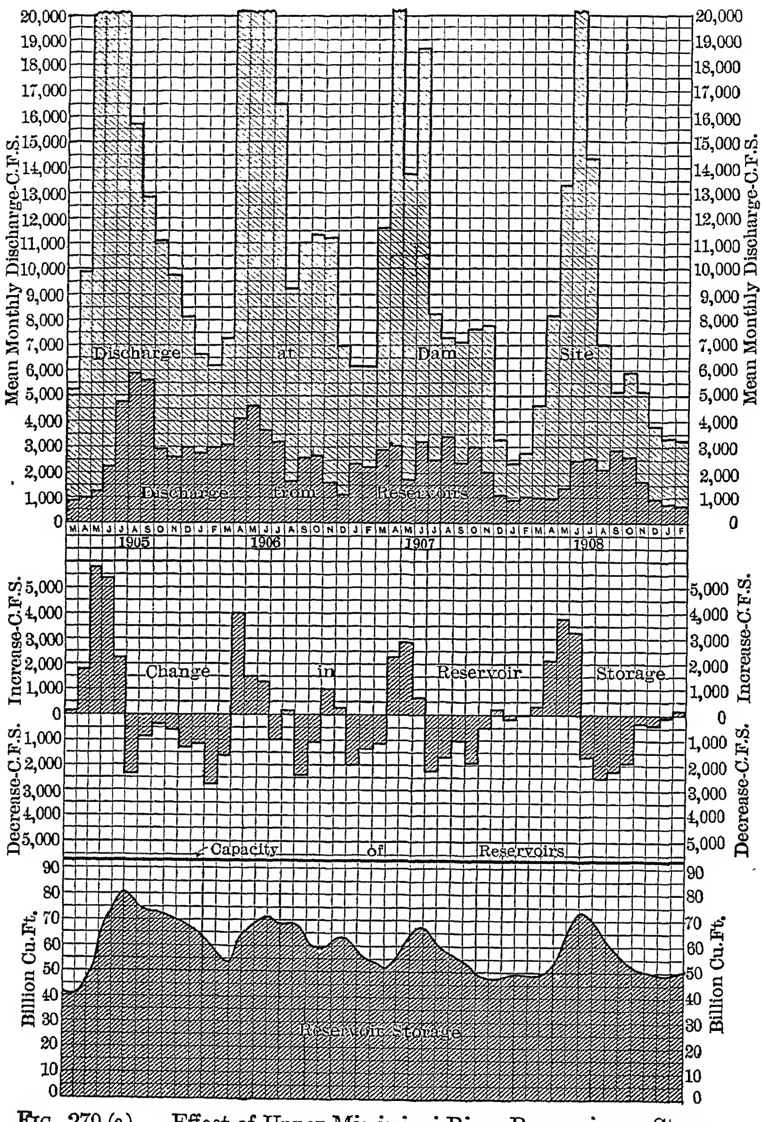


FIG. 279 (a).—Effect of Upper Mississippi River Reservoirs on Stream Flow at Minneapolis, Minn.

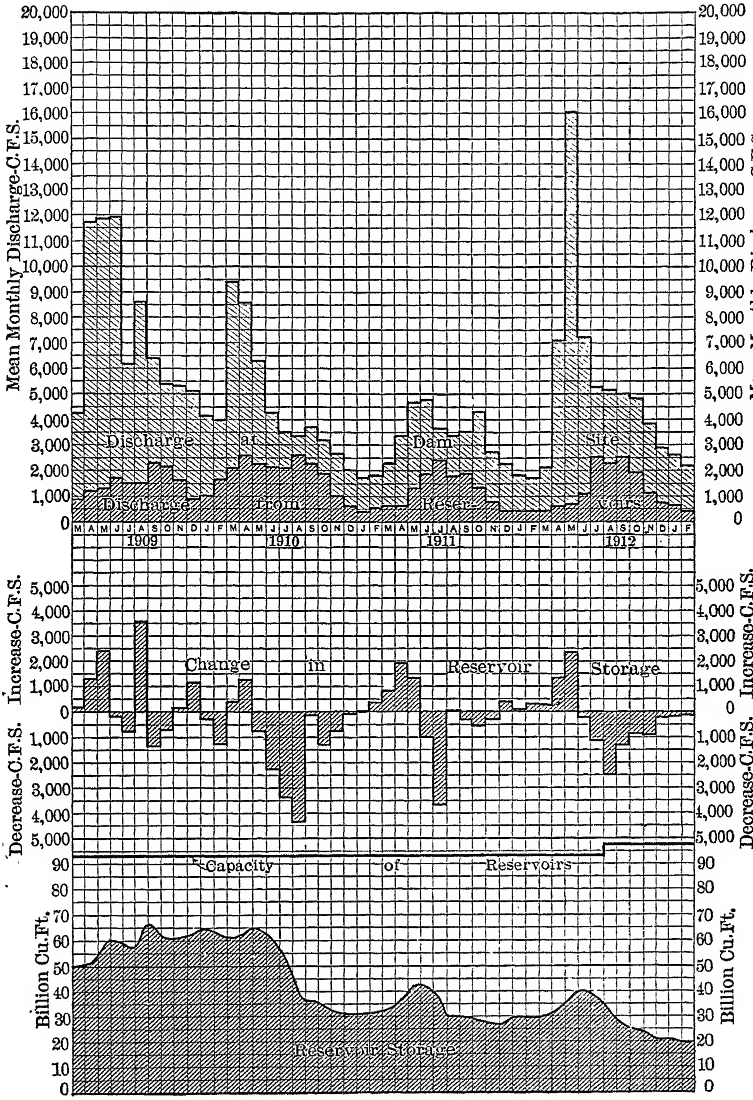


FIG. 279 (b).—Effect of Upper Mississippi River Reservoirs on Stream Flow at Minneapolis, Minn.

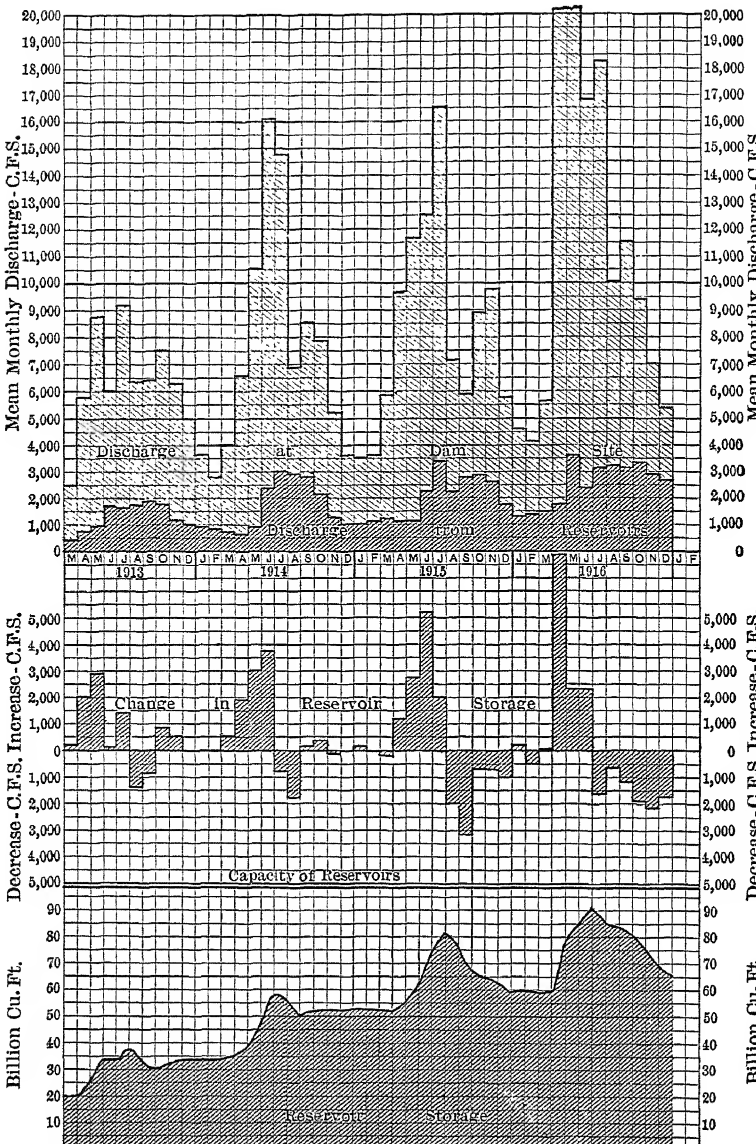


FIG. 279 (c).—Effect of Upper Mississippi River Reservoirs on Stream Flow at Minneapolis, Minn.

If the discharge of stored water is continued from one freshet to the next, the resulting retardation of seepage flow will reduce the available ground storage capacity and thus, to a very limited extent, affect the height of the succeeding freshet. On northern streams summer discharge from reservoirs will increase seepage flow during the following winter to the extent of the discharge that was lost in seepage during the summer. The effect on stream flow, of course, will be a maximum immediately after the reservoir discharge ceases. Slight indications of such reappearances of seepage loss appear in the data of Fig. 279 for the Upper Mississippi River reservoirs.

Evaporation Loss in Channels. — The evaporation loss from reservoirs discharging through natural channels is usually negligible. Such loss is limited to the evaporation from the *increased width* of the stream, resulting from the increased stage. Only in rare instances does the discharge of stored water from reservoirs result in increasing the width of the conveying channels by more than a few per cent. In the case of artificial channels, of course, the evaporation loss from the entire water-surface must be deducted from the reservoir discharge in determining the effective portion.

Other Factors. — Other factors deserving consideration in determining the effectiveness of reservoir discharge in particular instances will be discussed in connection with the several purposes for which stored water is used.

Storage for Municipal Purposes

For Water-supply Purposes. — The storage of water which is most far-reaching in its effects is storage for municipal purposes. A great many municipalities are entirely dependent upon stored water for their municipal water-supply. Prominent among these are New York and Boston on the Atlantic Coast, and San Francisco and Los Angeles on the Pacific. As the quantities of water ordinarily required for domestic consumption are relatively small, the provision of the necessary

storage capacity is entirely practicable. Greater New York, for example, with its millions of people and all its manufacturing establishments uses about 1000 cubic feet of water per second.

As the low-water supply is often insufficient even to balance the evaporation from the reservoir surface, it is not unusual for municipal water-supply reservoirs to control the entire ordinary runoff from the tributary watershed, and to effect equalization of flow over a period of several years. McCulloh* states that the runoff from the Croton River watershed, New York, is so thoroughly controlled that nine tenths of the entire yield is utilized. A comprehensive paper entitled "Storage to be Provided in Impounding Reservoirs for Municipal Water Supply" by Allen Hazen, in which the law of probabilities is applied to the storage problem, appears in Vol. LXXVII, p. 1539, Trans. Am. Soc. C. E.

For Improving Sanitary Conditions. — The release of stored water to increase the low-water flow is also effective in improving the sanitary condition of streams into which relatively large quantities of sewage are being discharged. Similarly, a reduction in hardness and acidity may be secured in the case of streams into which mine drainage and manufacturing wastes are being discharged in large quantities. At low-water stage the Monongahela River at Pittsburgh, for example, is so acid, primarily as the result of mine drainage, that carbon steel plates on lock gates become badly corroded in two years, and even nickel-steel plates last only about four years.† Unsanitary conditions prevail on many eastern streams. A typical project for the improvement of these conditions is that proposed for the Naugatuck River, Conn.‡ Three reservoirs with a combined capacity of 1.75 billion cubic feet are proposed for the purpose of increasing the extremely small low-water flow of this stream which has virtually become an open sewer.

* McCulloh, Walter, Conservation of Water, p. 61.

† Report of Pittsburgh Flood Commission, p. 248.

‡ Engineering Record, Apr. 29, 1916, p. 573.

Storage for Irrigation

The Committee of the American Society of Civil Engineers on "A National Water Law" in its preliminary report of January, 1916, places the use of water for crop production next in importance to its use for household purposes. With this view, the author is in accord. No other use of water can yield an equal return in the necessaries of life.

Aside from the small irrigation systems connected with truck farms in the East, irrigation projects involve large expenditures of money and the storage of large quantities of water. Under the direction of the Federal Reclamation Service irrigation has, in recent years, made great progress. The third largest reservoir in the world, that at Elephant Butte, New Mexico, with a capacity of 115 billion cubic feet, is among the great reservoirs built by the Reclamation Service for the storage of water for use in the irrigation of arid lands.

On account of the large evaporation and seepage losses from reservoirs and canals and in the irrigated fields themselves, large quantities of water must be stored on irrigation projects. As the need for irrigation is an indication of insufficient or ill-timed precipitation, and as in such regions the low-water flow of streams is usually previously appropriated and used, dependence must be placed on flood-water storage.

For storage purposes the flow of northern streams that rise in the mountains and are snow-fed is more dependable than that of more southern rain-fed streams. The freshets occur later on northern streams, and consequently there is less evaporation loss after storage. Freshets on rain-fed streams are very irregular, and usually occur early in the season.

As most rivers in the arid and semi-arid regions decrease in volume, through percolation and evaporation, as they spread out upon the plains, the best storage sites are in the upper valleys. Here the water-table is usually above the stream-bed, good dam sites are available, and by storing water to con-

siderable depth, the evaporation losses from the reservoir are greatly reduced.

Seepage from irrigation reservoirs and canals, and from irrigated fields, is manifesting itself in the increase of the low-water flow of streams in these regions and in the necessity for the drainage of low-lying lands.

Although considerable power is being developed on a number of irrigation projects, such use of the stored water is entirely secondary to its use for agricultural purposes.

Storage for Logging

One of the most extensive uses of stored water in the modification of stream flow is in connection with logging operations. Although the quantity of water stored in connection with each project is usually small, logging dams abound wherever logging operations are carried on. As the sluicing of logs is usually completed by midsummer, the stored water does not help to increase the late summer low-water flow. When logging dams are located in out-of-the-way places, the gates are usually closed in the fall so as to insure a good supply of water for the succeeding season. Such operation inevitably reduces the winter low-water flow and increases the spring high-water.

Storage for Navigation

Applicability. — The storage of water on navigable lakes for the maintenance of better stages on these lakes, and also the storage of water for feeding navigable canals, as in Lake Gatun, for example, has been successfully performed by different nations for many years. The increase of river stages through the discharge of stored water, however, has very limited application on account of the tremendous quantity of water required to effect substantial increases in stage on the lower, navigable, reaches of the streams. The discharge from storage reservoirs has less and less effect, in increasing river stages, progressively downstream. Usually the only feasible reservoir sites are

located near the headwaters of the streams. Where the effect is greatest, the stream is usually not navigable and when the navigable reach of the main stream is reached, the effect of reservoir discharge is usually very small. In portions of Europe where the streams are relatively short, water storage for increasing navigable stages has found some application, but nearly all projects applicable to the larger streams, both in Europe and in the United States, have been unfavorably reported upon. In Germany, where the greatest development of storage in the interests of navigation has taken place, no system of reservoirs used has a greater capacity than about 10 billion cubic feet. This naturally limits their effect to reaches of not more than two or three hundred miles of river.

The Two Largest Navigation Reservoirs. — There are two large reservoir systems in the world constructed and operated solely in the interests of navigation. The oldest of these systems is that in Russia, with a capacity of 35 billion cubic feet. The effect of this system of reservoirs is substantially limited to the 300 miles of river immediately below the reservoirs.

The largest system of reservoirs in the world constructed in the interests of navigation is the Upper Mississippi River system in Northern Minnesota. The combined capacity of the six reservoirs constituting this system is nearly 98 billion cubic feet. This is sufficient to store twice the average annual runoff from the tributary watershed.

Effectiveness of Navigation Reservoirs. — Fig. 279 shows the total amount of water stored in these reservoirs at the end of each month for the past 12 years, together with the monthly change in storage expressed in cubic feet per second, the monthly mean discharge from the reservoirs, and the discharge of the Mississippi River at the site of the Government Dam now under construction in the Twin Cities.

Table 45 shows the percentage of the total reservoir capacity that was utilized each year, together with the maximum and minimum storage and the month in which this occurred.

TABLE 45. — STORAGE UTILIZED EACH YEAR IN THE UPPER MISSISSIPPI RIVER RESERVOIRS

Year	Maximum quantity in storage during year		Draft on storage after filling reservoir		
	Date	Billion cu ft	Billion cu. ft.	Percentage of total capacity	Date of maximum draft
1905	August 1	81 6	28.3	29	April 1, 1906
1906	July 1	71 0	19 8	20	April 1, 1907
1907	July 1	66 8	19 3	20	December 1, 1907
1908	July 1	73 0	23 6	24	February 1, 1909
1909	September 1	66 8	5 6	6	March 1, 1910
1910	May 1	65 5	35 0	36	February 1, 1911
1911	June 1	42 2	14 9	15	December 1, 1911
1912	June 1	39 5	19 4	20	March 1, 1913
1913	August 1	37 9	7 9	8	October 1, 1913
1914	July 1	57 4	7 0	7	September 1, 1914
1915	August 1	80 2	21 4	22	March 1, 1916
1916	July 1	90 1	......	....	. ...

The storage of water during the early spring and its release in the interest of navigation during the summer low-water period is very apparent. It will also be noted, however, that very little water is discharged during the winter low-water period when there is the greatest demand for water-power and when the stream flow is the lowest, but that, on the contrary, some water is often stored during the winter months.

The discharge of stored water during the summer low-water months of exceptionally dry years, such as 1910 and 1911, has a marked effect on the stage of the upper 175 miles of navigable stream immediately below the three principal reservoirs. The commerce on this portion of the river is, however, extremely small. The next 150 miles of river, to the center of Minneapolis, are given over to power development and are not navigable. From Minneapolis and Saint Paul to Lake Pepin, a distance of about 70 miles, the effect of reservoir discharge is to increase the stage, during exceptionally dry years, from about 2 feet to practically nothing.* The effect on the stage of the remaining 2000 odd miles of the Mississippi River is, for practical purposes, negligible. Moreover, the increase in stage

* Final Report, National Waterways Commission, 1912, p. 193.

does not measure the increase in ruling depth. According to General Bixby, former Chief of Engineers, U.S.A.: *

> "On the Upper Missouri, within the limits of North and South Dakota, while there is often 3.5 to 5-foot draft at dead low water, there is only a draft of 3 feet at a 5-foot stage of water, the crest of bars rising with rising water. On the Mississippi River from St. Louis to Red River, where the natural unimproved depth over the bars is only about 4 feet, the rise of bar crests is about one-half the rise of the river, giving below St. Louis only 14 feet on the bars at a 20-foot stage above low water so that the benefit to navigation is rather illusory."

Furthermore, the increased stage in the Mississippi River between St. Paul and Lake Pepin is of value only when the ruling depth for boats coming upriver does not occur below Lake Pepin. It is evident that unless up-bound boats can reach Lake Pepin the increased stages in the river above that lake have little commercial value.

Storage for Flood Prevention

Applicability. — The applicability and the limitations of the storage of water for flood prevention purposes are determined by the causes and the characteristics of the floods of each given stream. This fact will be appreciated from the previous discussion of precipitation and the hydrographs of floods on typical streams. On some streams of the country floods occur in winter; on others in spring, summer or fall. A great flood may be preceded by one of ordinary magnitude or two great floods may follow each other within a relatively few days. To be effective, then, flood water must be stored only temporarily lest the storage capacity be unavailable when most required. Storage capacity that is utilized for holding water over from

* Bixby, Gen. W. H., Final Report National Waterways Commission, 1912, p. 193.

one year to the next cannot be said to be available for flood prevention purposes.

Methods. — Three principal methods are in use for temporarily storing water in order to reduce the flood flow of streams. Two of these methods are entirely automatic in operation and accomplish their object either through the utilization of check dams or through "retarding" or "detention" basins. The other method employs impounding reservoirs with manually operated gates for discharging the stored water at will.

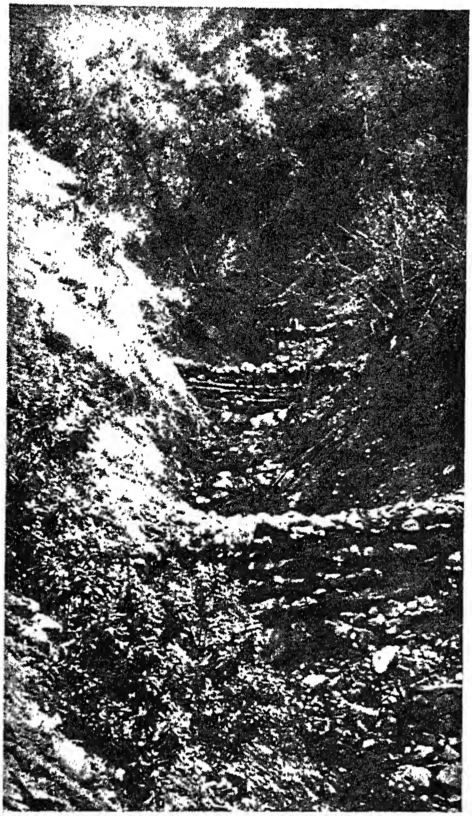
Check Dams. — Check dams of the type used for preventing erosion and floods in the mountainous regions of Austria, Japan, and Switzerland are now being tried out in California in a region where the rivers fall about 6000 feet in 40 miles and carry a great deal of gravel, sand, and silt, which is deposited in the form of debris cones where the streams issue from the canyons.*

The object of check dams is to retard the flow of water down the ravines and canyons that comprise the upper watersheds of torrential streams, thus reducing erosion, and to encourage the greatest possible absorption of water in the ravines themselves, and in the debris cones at the mouths of the canyons. Check dams are relatively small, simple, and inexpensive, being constructed mainly of loose rock. Typical dams built in California under the direction of Olmsted † are shown in Fig. 280. Most of the experimental work is being done in Haines Canyon, which drains an area of 1.45 square miles of burnt-over, mountainous land. Although in 1914 this canyon yielded 712 second-feet per square mile, which is the highest unit runoff ever recorded in southern California, the heavy rains of January, 1916, after the construction of 384 small check dams at an average cost of about $12 each, yielded only 113 second-feet per square mile as compared with much larger unit yields

* Engineering News, Feb. 10, 17, and Mar. 23, 1916; Engineering Record, May 13 and 20, 1916.

† Olmsted, F. H., Consulting Engineer, Los Angeles, Calif., Member of Los Angeles Flood Commission.

from larger, untreated watersheds in the same locality. The extent to which these experimental check dams have increased the absorption of water is indicated by the growth of vegetation in the canyons and the fact that canyons which were previously dry at low water are now yielding a small low-water flow.



Courtesy Engineering Record.

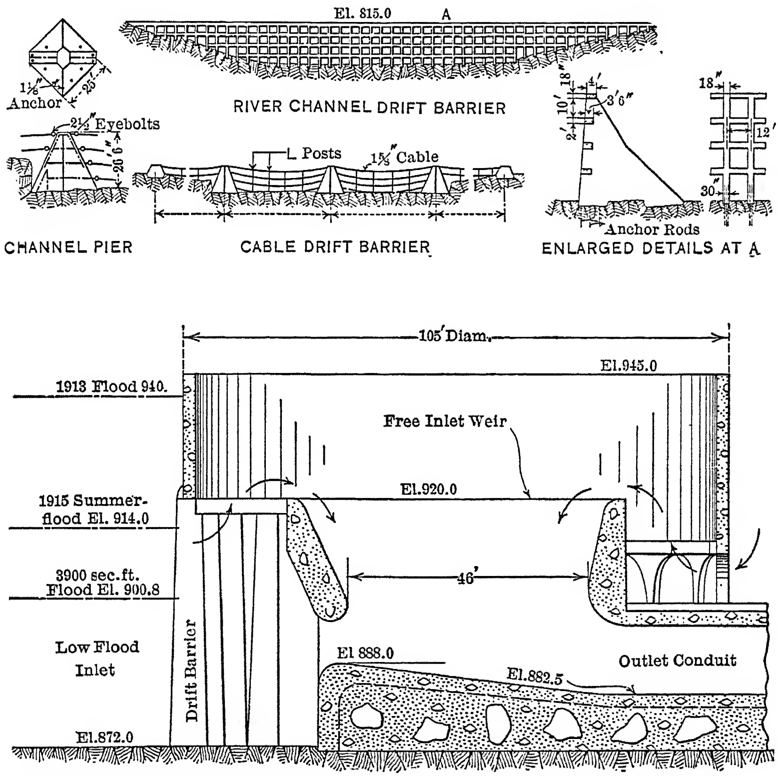
FIG. 280. — Typical Check Dams.

While check dams are unquestionably effective aids in the control of flood runoff from small precipitous watersheds where the rock does not lie close to the surface of the ground, the quantity of water which can be controlled in this way is com-

paratively small so as to severely restrict the applicability of these dams for flood prevention purposes.

Retarding Basins. — Retarding or detention basins are somewhat similar in their action to check dams but of much larger size and of wider applicability. The first projects in the United States employing retarding basins on a large scale are those for the protection of the Miami and the Franklin County Conservancy Districts from the floods of the Miami and the Scioto rivers in Ohio. Typical cross-sections of the dams proposed for the retardation of extreme floods on these streams are shown in Figs. 281 and 282. Retarding basins act in a manner essentially similar to that exemplified by the action of natural lakes in that no definite limit is placed, either for the stage which water in the basin may reach or the maximum rate of outflow from the basin. Both are entirely dependent upon, and increase with, the magnitude of the flood inflow. In contrast with most natural lakes, however, no permanent storage of water is provided for and the fluctuations in stage and outflow are very rapid. The intention is to permit all ordinary floods to pass through the controlling dams unhindered and to merely retard or detain rather than to impound the water of *extreme* floods. In consequence the land within the basin may be used for agricultural purposes but no buildings nor other improvements should be permitted within the basin. As indicated in Fig. 281 the discharge openings in the dams are carefully protected by barriers to prevent their being clogged by floating debris, and ample, free spillway capacity is provided, in addition to the openings through the base of the dams, to prevent the possibility of the overtopping of embankments at times of unprecedented floods. The action of a retarding basin in taking off the crest from a serious flood is well shown in Fig. 283. Since the reduction of flood peak and retardation of flood water result in prolonging the flood flow from the basin, thus producing considerably higher than natural stages in the tributaries for several days after the natural flood peak, the effect of re-

tarding basins on the floods of the main stream into which these tributaries feed should always be studied. This is particularly necessary in those instances where the retarding basins occur on the lower tributaries of a stream lying in a region



From Report of Alvord and Burdick, Franklin County Conservancy District.

Delaware Basin on Olentangy River, Tributary of Scioto River, Ohio.

Fig. 281. — Drift Barrier, Weir and Outlet Conduit of Typical Retarding Basin.

in which the flood-producing rainstorms pass upstream, and also, on the other hand, in some instances in which the retarding basins occur on the upper tributaries of the main stream and the flood-producing rainstorms travel downstream.

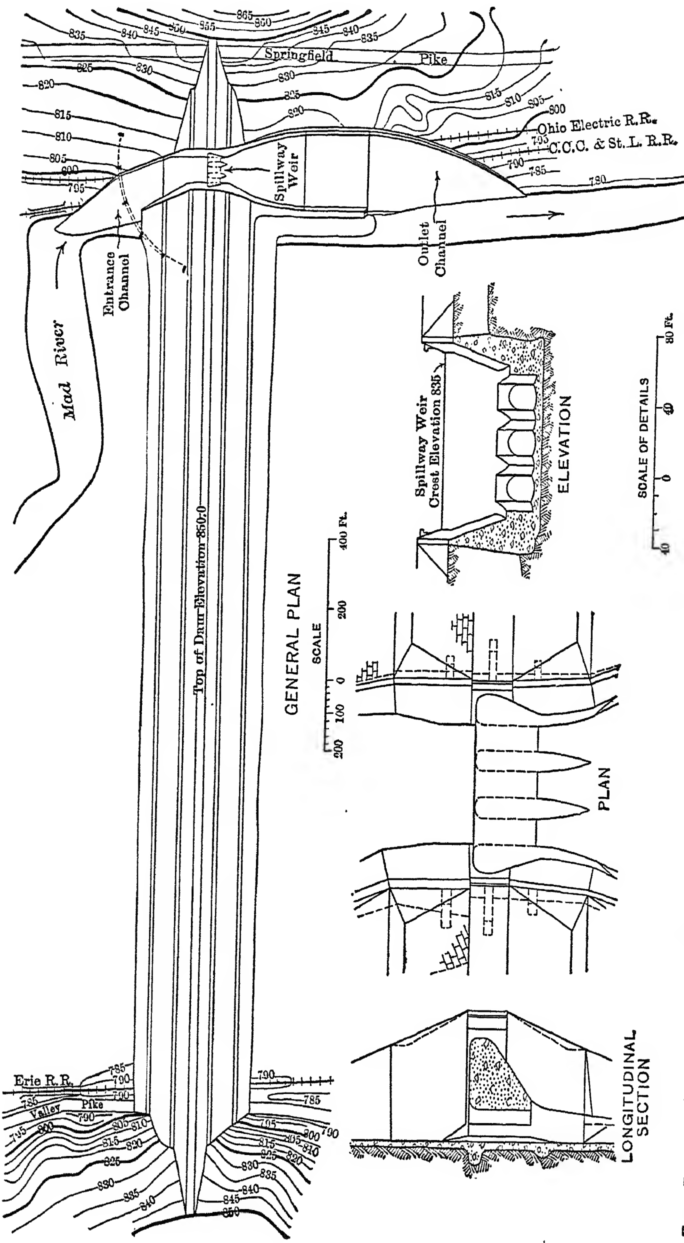
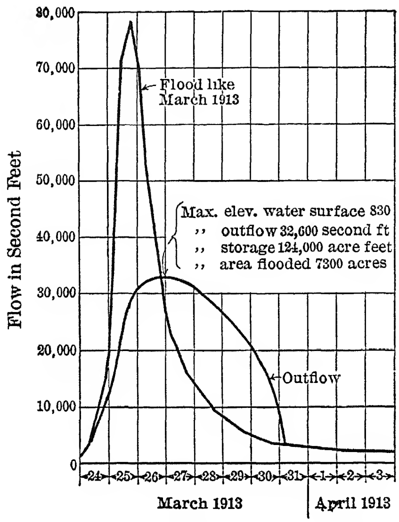


FIG. 282. — Dam, Spillway and Outlet Conduits of Typical Retarding Basin

Huffman Basin on Mad River, Tributary of Great Miami, Ohio.

From Report of Arthur E. Morgan, Miami Conservancy District.



From Report of Arthur E. Morgan, Miami Conservancy District.

Proposed Huffman Basin on Miami River.

FIG. 283. — Action of Typical Retarding Basin in Taking Crest off Flood.

Impounding Reservoirs. — The more permanent storage of flood water in impounding reservoirs, from which it can be released at will, is usually more expensive in both construction and operation than more temporary storage in retarding basins. Where impounding reservoirs are used, an attempt is usually made to conserve and utilize at least some of the stored water for increasing the low-water flow. This, however, necessitates the permanent withdrawal of flowage lands from agricultural use, and constant attendance at the dams. Unless it is strictly understood that the reservoir capacity provided for the storage of flood water shall not be utilized for permanent storage, such combination of storage purposes usually results in an ultimate defeat of the object for which the reservoirs were built. To be effective for flood prevention, reservoirs must be kept as nearly empty as possible.

From the very nature of their use, flood-prevention reservoirs are extremely limited in scope. They are applicable only to

small watersheds of a few thousand square miles in area, the flood runoff from which reaches the streams a few hours after the rains fell. The storage of sufficient water to appreciably reduce the flood flow of large streams would require the withdrawal, from agricultural use, of areas of land quite disproportionate to the benefits that can possibly be secured from such storage. Moreover, reservoirs can seldom be located so as to be effective in preventing floods below a point on the stream where its drainage area is more than two or three times the area of watershed tributary to the reservoirs. Floods on the tributaries of a stream are practically never synchronous. Floods on small streams are due to excessive rains over restricted areas, and these rainstorms may center just outside of the reservoir controlled area, as happened during the Merrill, Wisconsin, storm of July, 1912, which produced a record-breaking flood at Wausau, Wisconsin, but hardly an appreciable increase in runoff from the watershed draining into the upper Wisconsin River reservoirs.

Floods on large streams result from protracted, well-distributed rains that yield comparatively little water for storage at the headwaters of the tributaries where reservoir sites are available. To be effective in preventing floods on large streams reservoirs should be located a considerable distance downstream on the large tributaries. In such localities, however, the land is usually improved and very valuable for other purposes.

Control of Mississippi River Floods by Reservoirs. — The floods on the Lower Mississippi River cannot be prevented by reservoir storage on account of the tremendous quantities of water involved. This has been well stated by Col. Townsend * in the following words:

> "To have retained the Mississippi flood of 1912 within its banks would have required a reservoir in the vicinity of Cairo, Illinois, having an area of 7000

* Townsend, Col. C. McD., President Mississippi River Commission, in address before National Drainage Congress, St. Louis, Mo., Apr. 11, 1913.

square miles, slightly less than that of the State of New Jersey, and a depth of about 15 feet, assuming that it would be empty when the river attained a bankful stage."

The cost of such a reservoir would, of course, be prohibitive. The only economical sites for reservoirs are near the headwaters of the streams, and here reservoirs are relatively ineffective.

The ineffectiveness of reservoirs at the headwaters of the Mississippi River system, for flood prevention in the lower reaches, is well indicated by the fact that during the 1912 flood, when the river at Cairo had risen about 50 feet, the upper Mississippi at St. Paul was contributing little more than a thousandth part of the flood water; the Ohio River at Pittsburgh was contributing about a hundred-and-thirtieth part of the floodwater at Cairo; and the Missouri River at St. Joseph was contributing about a hundred-and-twentieth part. If all the water of these tributaries at the points mentioned had been held back by reservoirs, it would have lowered the river at Cairo by only a few inches during a fifty-foot flood.

Such complete control of the upper Mississippi, the upper Missouri, and the upper Ohio rivers, however, cannot be accomplished by even the most extensive reservoir construction, unless these reservoirs are to be built in populous agricultural communities, right outside of the large cities, and then only at a cost entirely incommensurate with any benefits that could possibly be derived therefrom.

The small effect of the upper Mississippi River reservoirs on the flood flow of this stream is well indicated by the fact that if these reservoirs had not been in existence in 1905, the total natural flood flow from the lakes constituting these reservoirs, at the time of the crest of the 1905 flood at Minneapolis, would have been less than one tenth of the total flood flow. The actual outflow from the reservoirs was about one half the natural, so that the effect of the reservoirs was to reduce the

flood flow at Minneapolis by less than 5 per cent. Moreover, in the same year (1905) these reservoirs could not even prevent a flood at Aitkin, Minnesota, on the river about 100 miles below, much less at the Twin Cities, or at Cairo, Illinois, or Memphis, Tennessee. On July 1 of that year, when the flood at Aitkin, Minnesota, was practically at its highest, the reservoirs were discharging little more than their winter flow. The flood had been produced by the tributaries which enter the Mississippi between the reservoirs and Aitkin, notwithstanding the fact that the reservoirs control 61 per cent of the watershed above Aitkin. Nevertheless, during moderate floods on the upper river, resulting from general rains, the upper Mississippi Reservoirs often have an appreciable effect in reducing flood flow, as indicated by the hydrographs of Fig. 205.

Engineers are agreed that flood flows on large streams cannot be prevented. The best that can possibly be done is to prevent overflow by confining the flood waters by means of levees, and by straightening and enlarging the channel at critical points, provided the character of the material will permit increased velocities, or the shore protection required as the result of these increased velocities can be placed at reasonable expense.

Storage for Power

Applicability. — Irregularities in water supply make the storage of water for power purposes of wide applicability. The greatest demand for power usually occurs at the time when the stream flow is the lowest. Similarly, irregularities in the demand for power, both during the day and during the year, make storage and pondage a valuable asset of every water-power development. The greater the head capable of development at any given site the greater the value of a given amount of storage. While the value of a stream for power development purposes is usually dependent more upon its minimum flow than upon its average utilizable flow, yet the opportunities for storage are seldom sufficient to warrant the use of stored

water entirely for increasing the dependable flow of the stream, as opposed to increasing its utilizable flow. In other words, the available storage capacity will usually yield a larger return on the investment if used each year for the purpose of increasing the flow of the stream up to its limit of economical utilization than if used for the purpose of holding water in storage for several years with a view to increasing the extreme low-water flow, and, consequently, the dependable flow which determines the maximum amount of power available at all times.

Limit of Economical Development. — On most streams of the United States the variation in stream flow is so great, even considering all the equalization that can economically be effected by storage, that it usually pays to install turbine capacity sufficient to utilize considerably more than the low-water flow. Just what proportion of the time water must be available to permit of its economical use in power development depends upon the relation between the *fixed charges plus operating cost* of the additional water-power plant capacity required to utilize water available less than 100 per cent of the time, and the *operating cost* of a steam, gas, or other auxiliary power plant. Merely the *operating cost* of the auxiliary plant should be used in making the comparison because this plant is required, in any event, to carry part of the load at time of low water.

Size of Auxiliary Power Plant. — The size of auxiliary power plant required for supplementing the water-power at low water, without reference to insurance against interruptions in service from other causes, depends upon the daily variations in load and the storage, or more properly "pondage" available at the plant. When sufficient pondage is available and a plant is carrying the usual light and power load, the water-power plant can be used to full capacity during the time of peak load, and the steam plant can be run as nearly continuously as possible. With this combination, the required size of auxiliary power plant is usually reduced to about half of that which would otherwise be necessary to supplement the water-power de-

veloped from the low-water flow of the stream. When the water-supply is ample, the auxiliary plant can be used to carry the peak of the early evening load and the water-power plant run as nearly continuously, at full load, as possible. These considerations are basic to a proper understanding of the subject of the modification of stream flow for water-power purposes by means of storage and pondage.

The Mass Curve. — The best method of studying the effect of reservoir storage and pondage on stream flow is by means of the "mass" or "flow-summation" curve. This is a diagram which shows the net available amount of runoff or supply to the reservoirs, expressed in any convenient unit, which has accumulated in any given period of time. The slope of the tangent to the mass curve at any point indicates the net rate of runoff or inflow at that time. In summing up the runoff, the increment for a day, for ten days, or for a month may be used, depending upon the regularity in the flow of the stream and the available storage capacity. In the case of natural lakes the runoff records, that is, the outflow plus or minus storage on the lake, give the net inflow directly. In the case of artificial reservoirs the evaporation and seepage loss must first be computed and deducted from the observed or estimated runoff.

It is particularly important that the mass curve be constructed from the *net available inflow*, especially in the case of natural lakes, so as to eliminate evaporation and seepage losses and the effects of natural regulation.

Two typical mass curves used in connection with the study of a large storage project are shown in Figs. 284 and 285. The volume of runoff or inflow into Rainy Lake is expressed in cubic feet and summed up by months. Tangents drawn to the mass curves at various points indicate rates of regulated outflow from the reservoir. Every point on these tangents represents the regulated outflow up to the given time and the point on the mass curve, directly underneath, represents the inflow up to the same time. The vertical distance between

the two points, therefore, represents the difference between inflow and outflow, or draft on storage. Since the area of the reservoir is known the draft is readily converted into reservoir stage, when this is desired. A full reservoir is assumed at the beginning of the period. The vertical height of the cross-hatched areas represents the volume of non-utilized flow or water wasted.

Regulation to Increase Dependable Flow. — Two methods of utilizing the reservoir storage are shown in Figs. 284 and 285. Under the first method of regulation, styled "Method A," the aim is to utilize the available storage in securing the maximum possible increase in extreme low-water flow over a period of years, that is, to increase the *dependable* flow. Since it is absolutely impossible to forecast the runoff from the tributary watershed for any considerable time in advance, the maximum permissible rate of discharge, when stored water is being drawn upon, is limited to the dependable rate, that is, the rate which can be maintained on the available storage over the most extreme dry period of years to be expected. When water is being wasted, a higher rate may sometimes be utilized to advantage. In the case of Rainy Lake, the maximum rate which can be economically utilized is about 10,000 second-feet as turbines aggregating this capacity have already been installed. Whenever stored water is being drawn upon the outflow must be limited to the dependable rate or the reservoir may not be full at the beginning of the dry period which, in this instance, extended over 3 years for the case of 100 billion cubic feet of available storage, and over 5 years for the case of 150 billion storage.

Regulation to Increase Utilizable Flow. — Under the second method of regulation, styled "Method B," the aim is to utilize the available storage in securing the maximum increase in the ordinary low-water flow, without endeavoring to substantially increase the extreme low-water flow, *i.e.*, to increase the *utilizable* flow. Under such regulation of stream flow the aim is to use as much of the available storage capacity each year

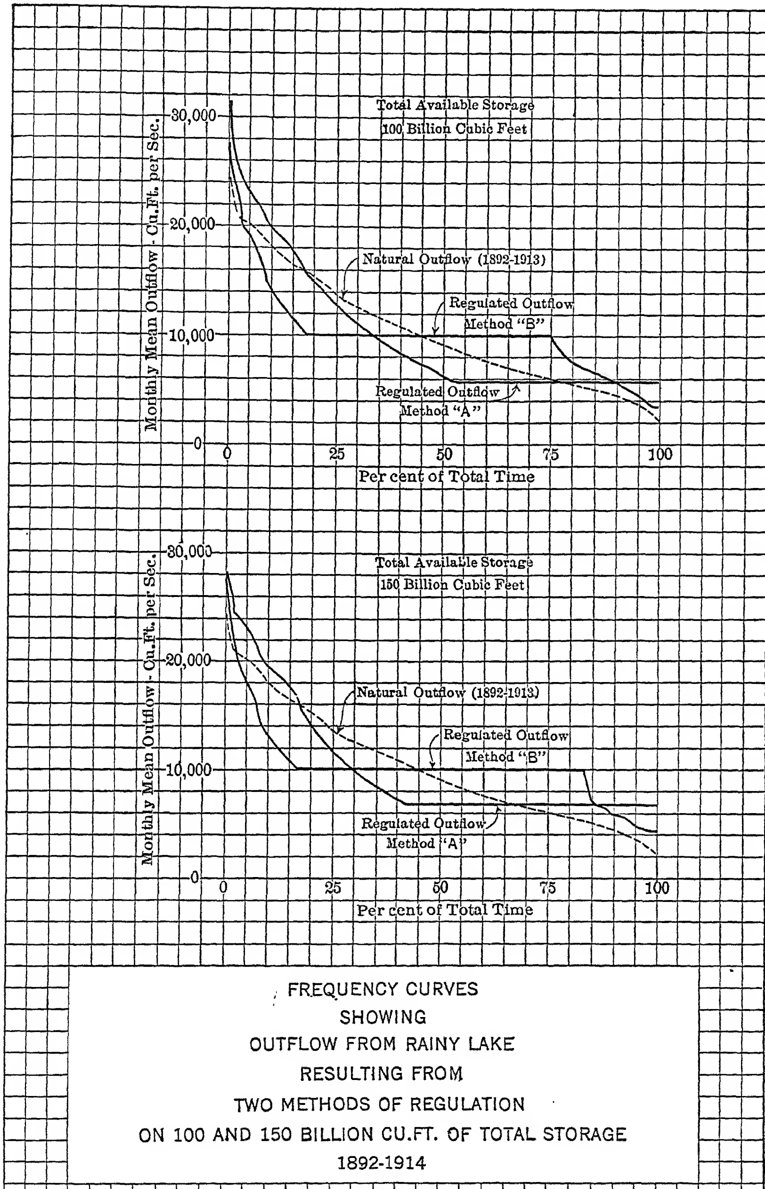
as possible, drawing upon the stored water at as high a rate as can economically be utilized by the given installation.

Under "Method A" the available storage capacity would have been fully utilized only once during the 22 years. Under "Method B" 100 billion cubic feet of storage would have been fully utilized ten times in 22 years and 150 billion cubic feet of storage would have been fully utilized five times, but the reservoir would not have been full at the beginning of the extreme dry period so that during this period the reservoir storage would not have materially increased the natural low-water flow.

Mass-curve studies which assume a variable rate of discharge for each dry season and are premised upon a use of all, or nearly all, the available storage capacity during each dry season, are entirely theoretical and have no practical application. They assume that the runoff can be accurately forecast for months and even years in advance.

Frequency Curves. — Frequency curves showing the extent to which the outflow from Rainy Lake could have been modified by these two methods of regulation are shown in Fig. 286. "Method B" results in a much greater increase in utilizable outflow than "Method A" but does not produce any substantial increase in low-water flow. Even if the demand for power is constant, so that auxiliary power must be provided, "Method B" gives the better return on the investment in this instance. If the demand for power varies, that is, if the load factor is less than 100 per cent, the advantage of "Method B" over "Method A" increases.

It appears from the frequency curves that, under "Method A," greater rates than the dependable rate would be available less than 50 per cent of the time and therefore hardly capable of economical utilization. In other words, under this method of regulation it usually would not pay to install greater turbine capacity than that required for the dependable rate, with possibly an additional spare unit in reserve.



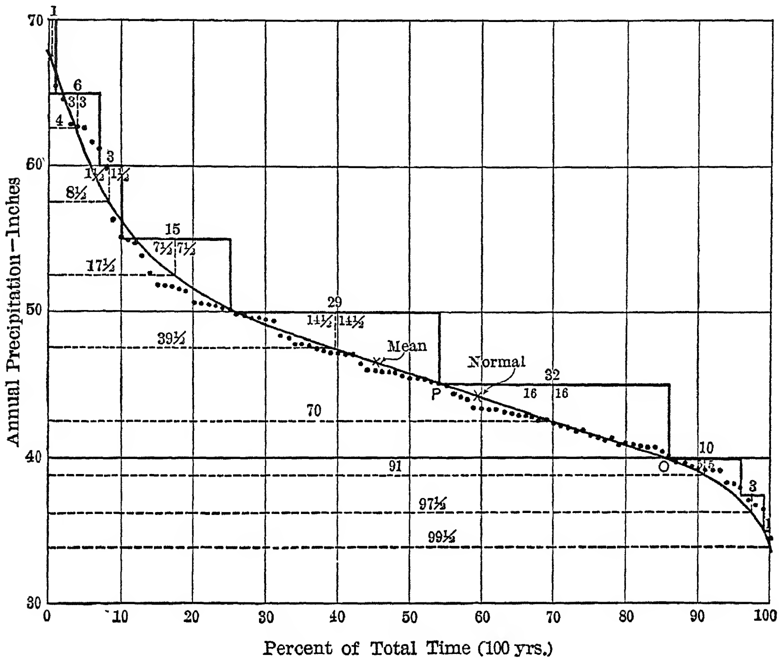
From Report of Adolph F. Meyer and Arthur V. White, Cons. Engrs., International Joint Commission.

FIG. 286.

When the available storage capacity is so large, however, as on Lake of the Woods, for example, where it aggregates about 250 billion cubic feet, so as to make the dependable outflow obtainable with the given storage about 80 per cent of the utilizable outflow obtainable with the same storage, regulation according to " Method A " is preferable to regulation according to " Method B " because the value of the increased power secured from the larger installation would not compensate for the cost of the auxiliary power plant required under " Method B " to supplement the water-power at times of low water.

Construction of Frequency Curve. — The frequency curve is a graph of data arranged in the order of magnitude. Any point on the frequency curve indicates the percentage of the total number of records of the given phenomenon which are greater than the value of this point and the percentage which are smaller. The point *P*, for example, on the frequency curve of Fig. 287, showing the frequency of annual precipitation at New Bedford, Massachusetts, from 1814 to 1913, indicates that 54 per cent of the total number of records of annual precipitation were greater than 45 inches and 46 per cent were smaller. The portion of the curve *P–O*, for example, indicates that in 32 per cent of the total number of years the rainfall was between 40 and 45 inches. The table accompanying the diagram of Fig. 287 and the construction lines and dimensions on the diagram itself indicate the procedure in working up data into a frequency curve. The size of groups to be selected in subdividing data depends upon the number of records available and the rate of variation in the records as the high and low values are approached. Usually it is desirable to use smaller groups near the two extremes in values than in between so as to get the correct curvature for the graph. In order to show how nearly correct the resulting graph is the actual values for the 100 years records at New Bedford have also been plotted in Fig. 287. The smoothed curve as drawn undoubtedly represents the actual facts better than a curve

which follows the observed values more closely, and will fit the records of 200 years better than such a curve.



	ANNUAL PRECIPITATION—INCHES NEW BEDFORD, MASS. 1814–1913								
Ordinate	67.5	62.5	57.5	52.5	47.5	42.5	38.75	36.25	33.75
Group	65.0 69.0	60.0 64.0	55.0 59.0	50.0 54.0	45.0 49.0	40.0 44.0	37.5 39.0	35.0 37.5	32.5 35.0
No. of Records in Group	1	6	3	15	29	32	10	3	1
Cumulative Total	1	7	10	25	54	86	96	99	100
Abscissa (No. of Records)	0.5	4	8.5	17.5	39.5	70	91	97.5	99.5
Abscissa (Percent)	0.5	4	8.5	17.5	39.5	70	91	97.5	99.5

FIG. 287.—Typical Frequency Curve Showing Method of Construction.

It is usually impracticable to plot the observed data in the exact order of magnitude. The grouping system, on the whole, gives better results and is incomparably faster. Where several thousand records are used as the basis for a frequency curve, no other method is practicable.

The mean annual precipitation at New Bedford is 46.45 inches. This amount of precipitation, however, does not occur with the greatest frequency and therefore is not the most likely to occur in any one year, that is, it is not the "normal" precipitation. Taking the curve as the basis, annual precipitations of from 40 to $48\frac{1}{2}$ inches occur with equal frequency so that the normal precipitation is $44\frac{1}{4}$ inches, or preferably between 40 and $48\frac{1}{2}$ inches.

Frequency of occurrence in per cent, as taken off the curve, can readily be converted into one occurrence during an interval of a certain number of years. For example, a precipitation of 56 inches was exceeded 10 per cent of the time, that is, a precipitation of 56 inches was exceeded, on an average, once every 10 years.

Conflict of Storage Purposes

Perhaps no more far-reaching misconception regarding an engineering problem is current to-day than that the water of rare and extraordinary floods can be conserved and used in the interests of power and navigation, of flood prevention and irrigation, or in the interests of other combinations of two or three different storage purposes at one and the same time. In the first place, to be really worth conserving, flood water should be available at least once in 3 or 4 years. Flood water that puts in an appearance once in 10, 15, or 20 years must be wasted quickly and with as little damage as possible. The fixed charges on the cost of the structures and facilities required for the utilization of water which is rarely available far exceed any possible benefit to be derived from such use. It is safe to say that on no stream in the country do really destructive

floods occur with a frequency which makes the flood water worth conserving. Storage for flood prevention, then, must be planned with that as its sole object. It does not follow, however, that reservoirs for flood prevention and other purposes cannot be, in many instances, economically combined in a single project. In other words, instead of building several distinct reservoirs, the upper portion of one reservoir may be reserved for use in storing or retarding extraordinary floods, its full capacity never being exhausted, however — not even once in a century. Another portion of the same reservoir may be in continuous use for storing water to supply the *ordinary* demands of power, navigation, or other purposes. Still another portion of this same reservoir storage capacity may be utilized for storing water that may not be required more than once in 25 or more years, to assure a predetermined, extreme low-water outflow from the reservoir. A fourth portion of the reservoir storage may be absolutely permanent and may serve merely to maintain sufficient head at the outlet to permit the development of a certain amount of power. The last condition seldom prevails. It is economical to permanently store water for the production of head capable of use in water-power development, only when the area of the reservoir becomes greatly reduced as zero storage is approached.

Another reason why reservoir storage designed for flood prevention cannot also be used in the conservation of water, is because a reservoir operated for flood prevention should be kept as nearly *empty* as possible and should not be used to store *ordinary* floods that occur every few years. Floods occur with great irregularity, and at different seasons. Severe rainstorms occasionally follow each other in rapid succession and travel the same paths. If reservoirs calculated to prevent floods are permitted to fill with ordinary flood water, there is good prospect of no storage capacity being available when the extraordinary flood occurs.

Reservoirs operated in the interests of power, navigation,

and irrigation are filled as soon as possible in spring, and the stored water is drawn upon only when needed. As during wet seasons little water need be discharged for these purposes such reservoirs are nearly always full when danger from extraordinary floods exists. Moreover, if natural lakes are utilized for storage purposes, and if no storage capacity has been specially reserved for flood-water storage, these reservoirs must discharge the flood water as rapidly as it runs off from the tributary watershed. As in large natural lakes the flood inflow is always greater than the flood outflow, the conversion of such lakes into storage reservoirs for power, navigation, and irrigation purposes must necessarily increase extreme floods on the river below unless provision is made in the same project for storing the extreme flood-water runoff.

Storage Below Ordinary High-water Mark

On navigable lakes and rivers the Government of the United States holds an easement to use the riparian lands up to ordinary high-water mark, in the public interest. The right to use such lands is often granted to private corporations in connection with projects for water-power development that also further the public interest of navigation. Moreover, the Supreme Court of the United States has held * that Congress intended to provide that the common-law rules of riparian ownership should apply also to lands bordering on non-navigable streams. It is of interest, therefore, to consider the possibilities and the limitations of modifying the flow of streams by storage below ordinary high-water mark.

Ordinary High Water Defined. — References to some important court decisions defining ordinary high water appear below.† The gist of these decisions is that where the banks of a body of water are relatively steep, ordinary high-water

* Railroad Co. *vs*. Schurmeier, 74 U. S. 272.

† *In re* Minnetonka 56 Minn., 513, Erdman *vs*. Power Co., 112 Minn., 175 Dorman *vs*. Ames, 12 Minn., 457.

mark "is coördinate with the limit of the bed of the water; and that, only, is to be considered the bed which the water occupies sufficiently long and continuously to wrest it from vegetation, and destroy its value for agricultural purposes." When the banks are low and flat, ordinary high-water mark is to be considered "the point up to which the presence and action of the water is so continuous as to destroy the value of the land for agricultural purposes by preventing the growth of vegetation, constituting what may be termed any ordinary agricultural crop, — for example, hay." All stages that are "usual, ordinary, and reasonably to be anticipated" are within ordinary high-water mark but not "such extraordinary freshets as cannot be reasonably anticipated at particular periods of the year."

In most instances, ordinary high-water mark is difficult to determine. The extent to which land at a given elevation, bordering a body of water, is valuable for agricultural purposes, and the character of the vegetation found upon this land, varies from year to year, with the rainfall and other climatic conditions. If, in view of this fact, a conclusion respecting the possible agricultural use of riparian land must be premised upon records of meteorological phenomena, or of prevailing levels under natural conditions, extending over a considerable period of years, a definition of "ordinary high-water mark" directly in terms of observed hydrological phenomena must sooner or later find acceptance. The author has used the two following definitions in his practice. The results derived through the application of these definitions to a given group of data usually do not differ widely. According to the first definition, ordinary high water is the average of all stages above the average stage which prevailed during the agricultural season — that is, the planting, growing, and harvesting season. According to the second definition, high stages during the agricultural season are all those stages which are higher than the stage which was exceeded just 50 per cent of the time. Of the high stages,

ordinary high-water mark corresponds to that stage which was exceeded one half the time. In other words, ordinary high-water mark corresponds to that stage of a lake or a river which, on an average, was exceeded 25 per cent of the time during the agricultural season. As in other matters, judgment must be exercised in the application of these definitions to prevailing lake stages, and particularly to river stages.

Storage Limitations. — The extent to which stream flow can be regulated within ordinary high-water mark has unquestionably been greatly over-estimated. If, in the usual case of maximum natural inflow into a lake exceeding the maximum natural outflow, such a lake is held at ordinary high-water mark without increasing its outflow capacity, riparian property around the lake will be damaged during extreme high water, because the lake level is continuously higher than it would have been under natural conditions. If, now, the outflow capacity is increased so as to prevent the level of the lake, under any given flood conditions, from rising any higher than it would have risen, under the same hydrological conditions, with the outlets in a state of nature, the flood-water discharge from the lake will produce a stage in the channel below the outlet which will exceed the natural ordinary high-water mark. In other words, regulation of lake levels or modification of stream flow by storage below ordinary high-water mark is a physical impossibility.

When the banks of the channel below the outlet of the lake are high the damage from the greater flood-water discharge under regulation within ordinary high-water mark on the lake above may be negligible, even though the high-water mark in the channel below is considerably exceeded. Every case, however, must be considered on its own merits. Not infrequently, flowage rights must be secured both in the lake and on the discharge channel below the outlet.

NOTE TO TEACHERS OF HYDROLOGY

The author has purposely refrained from adding questions and problems to the several chapters of this book. An engineer who is qualified to teach the subject should also be qualified to frame intelligent and instructive questions. There are few colleges in which exactly the same amount of time is devoted to this subject. Usually the work is scattered through a half dozen different courses. The author believes that there is nearly as much reason for teaching hydrology as a fundamental course, instead of scattering the instruction through courses in water-supply, water-power, sewerage, drainage, irrigation, etc., as there is for teaching mathematics as a fundamental course. In view of this, an effort has been made to present the elementary subject-matter, accompanied by various methods of analyzing and interpreting data, and through these the elucidation of the fundamental principles of hydrology. It is not intended that assignments should be made page by page, although an effort has been made to develop the subject in a logical manner. Minor details have been omitted, and ample opportunity has been left for the work of the individual instructor.

A clear understanding of the factors that modify the flow of streams is absolutely essential to an intelligent use of stream-flow data. The author knows of no better way to crystallize the student's knowledge of these factors than to permit him to apply that knowledge in computing runoff from rainfall and other physical data. Watersheds coming within the student's observation should preferably be selected. Complete physical data should be available, including runoff records for at least a few years. To enable the students to fully grasp the work, the author takes them by groups and goes through the complete computations with them. When the classes are large, appointments are made so that one student is taken into the group and one excused about every hour, thus maintaining

a continuous organization of from 4 to 6 men, throughout an afternoon, for example. Each student first collects the necessary data and makes the preliminary evaporation and transpiration computations for one year. These data and computations are then taken in chronological order and the monthly runoff computed by the students in groups of four to six men, the instructor preferably taking the computation sheet in hand himself and assigning to the several students, in rotation, the daily temperature and precipitation records, the curves of surface and seepage flow, etc. Each student, under the supervision of the instructor, teaches his successor the work which he in turn is to do. Students not engaged on this work spend their time on other assignments until the computations for the entire period have been completed. A comparison is then made of computed with observed runoff, in case the fundamental curves of surface and seepage flow, etc., had been previously worked out by the instructor, and existing discrepancies analyzed with a view to determining the cause. The computed data, combined with such records of observed runoff as are available, are then used in the construction of a mass curve extending over at least twenty years, if possible, from which a study is made of different methods of modifying stream flow by reservoir storage.

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